Agricultural Salinity Consulting

Date: May 23, 2003

To: Kirk Dimmitt

From: J. D. Rhoades

Subject: Leaching and Irrigation Requirements in the Imperial Irrigation District

Objectives

At the request of Metropolitan Water District of Southern California, I joined its team of Water-Use Experts and made a number of assessments to estimate the on-farm water-use requirements of the Imperial Irrigation District (IID) for the period 1989-1996 and, more recently, for 2003, especially as related to soil and water salinity considerations. I was also requested to provide estimates of the volumes of tailwater and deep percolation being generated within the IID, using mass balance principles based on available data (which is limited mostly to 1994), and to compare these estimates to those of IID. These assessments and the key conclusions and major recommendations for year 2003 and for the mass balance evaluation are described and summarized here; they supplant those previously estimated based on 1989-1996 data (see February 21, 2003 Declaration of James D. Rhoades, submitted by Metropolitan in the IID litigation), since they are more thoroughly developed and current. Additionally, some USGS data of vertical deep percolation rate of IID soils are interpreted in terms of the IID leaching fraction, volume of deep percolation and tailwater volume; these results are also provided here.

Specifically, I was requested to: 1) determine the leaching requirement (LR) of the IID, 2) assess the leaching benefit of horizontal leaching associated with tailwater runoff, 3) calculate the on-farm requirement of Colorado River water for irrigation in IID using my determined value for leaching requirement and information on crop consumptive use and irrigation distribution efficiency/uniformity provided by other team members expert in these matters, and 4) assess the apparent leaching fraction (the fraction of applied and infiltrated irrigation water emerging as deep percolation) and the volume of tailwater being generated through irrigation with Colorado River water in the IID and discharged to the Sea, using salt balance principles, methods and available data, as another means to estimate the opportunity for water conservation in IID.

Summary

A. Overview of the Water and Salinity Budget Analysis

The on-farm water and salinity budget analysis, which comprises a component of my assessment, is a commonly used methodology to determine the amount of water necessary to sustain full yields for particular crops under various conditions. The on-farm water budget analysis recognizes that to sustain full yields, the inflows and outflows of both water and salts, with reference to the root zone of a particular crop, must keep the salt concentration in the soil water from becoming excessive for sustained plant growth. The analysis consists of determining the gain or loss in soil water and salinity content and concentration that occurs as a result of various inputs and outputs of water and salt, with reference to the crop rootzone. Although conceptually simple, the on-farm water balance approach requires detailed calculations and analysis to estimate the various inputs and outputs. While some inputs and outputs are relatively straightforward and easy to measure or estimate accurately, such as rainfall or crop ET, others are not. One such area is the amount of "leaching" that is required to keep the absolute salt concentration within the active crop rootzone from becoming too excessive to sustain plant growth. Associated with this area is a determination of the relative amount of leaching which is accomplished through "vertical leaching," in which salts are carried out of the rootzone through deep percolation, versus the amount which is accomplished through "horizontal leaching," in which the surface water dissolves some salt from the soil as it flows over the ground and carries it off in the tailwater.

B. Leaching Requirement of Imperial Irrigation District (IID)

The leaching requirement (LR) is the fraction of the infiltrated irrigation water that must leach through the crop rootzone in order to keep soil salinity within acceptable limits for full potential crop yield. The leaching requirement was estimated for the IID situation using two steady-state models. One of these models, the WATSUIT model, has been shown to provide very similar results to more exact but less practical transient models.

For year 2003 conditions, I estimated the leaching requirement for the IID-wide service area, taking into account the salinity composition and concentration of the irrigation water (Colorado River), the mixture of crops grown in the IID and their consumptive-use requirements corresponding to the average data of 2000-2002 and available standard crop salt-tolerance data. The LR value provided represents the overall "consumptive-use and leaching requirement" weighted District-wide LR_{infw} (referenced to the volume of infiltrated water) for the mixture all crops estimated to be presently grown there.

The IID-wide weighted values were calculated with the WATSUIT model (LR_W), which adjusts for the removal of salt from solution within the active rootzone by mineral precipitation, and with the conservative so-called traditional leaching requirement model (LR_T). Values for LR_W and LR_T were about 0.060 and 0.106, respectively. These values were based on Colorado River salinity equivalent to an EC value of 1.091 dS/m and on the weighted salt-tolerances, cropped acreages and consumptive use of each crop produced in the IID during the period 2000-2002. Because the former value is the more accurate, the latter is given for sake of comparison.

C. Benefit of Tailwater for Required Control of Soil Salinity

The IID has advocated that horizontal leaching and tailwater runoff is necessary for the control of soil salinity for about 87 percent of their irrigated fields and that the associated volume of tailwater should be credited as beneficial water use in the IID (NRCE, 2002). The methods used by IID to reach this conclusion are inappropriate. I have developed valid relationships to account for the effect of horizontal leaching combined with tailwater drainage in the determination of the leaching requirement and to quantify any beneficial effects of tailwater.

I present data that show that the district-wide LR_W is reduced from about 0.058 to about 0.056 by horizontal leaching, when the tailwater percentage is 15% (see Table 13a, where the footnote given describes the basis of this calculation). The percentage of the tailwater that contributes beneficially with the same effectiveness as deep percolation is only about 1 percent (3.7/335.6); the corresponding district-wide volume is only 3,700 acre-feet at a tailwater percentage of 15 percent (IID's regulated limit). The above benefits, as small as they are at 15 percent tailwater, are even less at lower tailwater volumes. Even though the horizontal leaching benefit is very low, I included it in all of my assessments of the on-farm water requirements. However, in comparison to the effectiveness of deep percolation in supplying the required leaching for IID fields and in comparison to the total LR, the impact and benefit of salt removal by tailwater is insignificant.

D. Requirement of Colorado River Water for On- Farm Irrigation

The calculation of the irrigation water requirement for IID requires knowledge of certain information concerning the crop water requirement (V_{et}), the effective rainfall (V_{rw}), the leaching requirement (LR_{infw}), the relative increase in salinity of tail water caused by salt removal from the soil (F_{ctw}; if horizontal leaching occurs and tailwater is allowed), the salinity of the irrigation water, the salinity-tolerances of the crops grown, the need to compensate for irrigation distribution inefficiency, which varies depending upon irrigation management, and the amount of additional water allowed to be lost.

With these factors in mind, I determined the on-farm water-requirement for the prevailing combination of net crop consumptive use (in excess of that provided by effective rainfall) and leaching requirement (including the benefit of horizontal leaching, assuming the F_{ctw} factor is 1.19 for the IID-wide situation; the basis for this value is given later). I applied a value of 0.95 for the non-uniformity factor (F_n). The non-uniformity factor is equivalent to the so-called distribution efficiency (Allen, 2003a), and accounts for incidental deep percolation of water in excess of that required for ET and leaching. I calculated the water requirement for three levels of tailwater percentage deemed appropriate by the MWD team, considering present and potential conditions. The three levels of tailwater were selected to permit the estimation of the water requirement of the IID service area that can be immediately achieved in 2003 by simply holding irrigators to a cap of 15 percent tailwater according to current IID regulations (this water requirement case is termed 15% _F_n = 0.95), as well as the water requirement given the implementation of relatively simple inexpensive management practices that can further reduce tailwater to 10 percent (this case is termed 10%_0.95) and with additional time and with somewhat more costly but still practical improvements reduce tailwater to 5 percent (this case is termed 5%_0.95). These estimates assume the salinity of the Colorado River, crop ET and effective rainfall values are constant.

The volume of Colorado River water required for delivery to farms in IID to meet all irrigation requirements for year 2003 conditions (excluding duck ponds and fish farms) without any reduction in crop acreage or yield is determined to be 2238 KAF +/- about 48 KAF, provided tailwater runoff is capped at 15 percent (as specified in IID regulations). The on-farm requirement for Colorado River water is increased by about 28,000 acre-feet to meet the additional needs of duck ponds and fish farms. The volume of tailwater corresponding to this case is 336 KAF. The farm delivery requirements for Colorado River water to meet on-farm cropping needs are reduced to about 2115 KAF for on-farm water management conditions achievable by 2005 and to about 2005 KAF for on-farm water management conditions achievable by 2009, as practical and achievable water management is implemented in the near future to reduce tailwater to 10 percent and 5 percent, respectively. The on-farm delivery requirement can be reduced even more with the implementation of more costly and time-consuming structural improvements. The volumes of tailwater corresponding to the 10 percent and 5 percent tailwater percentages are 212 and 100 KAF, respectively, where the tailwater fraction is based on the volume of on-farm delivery. The volumes of tailwater and deep percolation being discharged from the IID are described in the next section.

The volumes of Colorado River water required for diversions into IID, along with the on-farm irrigation requirements described above for 2003 (Table 13a), are given in Table 15. The total diversion water volume includes the additional volumes of Colorado River water required for duck ponds, fish-farms, M & I and miscellaneous uses and conveyance losses upstream of the farm headgate (the net diversion requirement) and the adjustment volume for estimated return flow credit (estimated return flow credit), along with the corresponding volumes comprising the Reinstated Order (as reported by Scott, 2003b). The total of these volumes represents the MWD-team estimates of the "Diversion Requirements" of Colorado River Water for each of the tailwater cases considered, in comparison to the Reinstated Order. After adjustment for return flows, the differences between the Reinstated Order and those for the three estimates equals the volumes of tailwater loss that can be conserved in IID, if not more. In terms of reduced diversions, these volumes are 291,317 (15% tailwater), 417,909 (10% tailwater) and 531,445 (5% tailwater) acre-feet, including additional water allotted for irrigation non-uniformity considerations.

E. Estimates of Volumes of Tailwater and Deep Percolation in IID

Based on the calculated requirement of on-farm irrigation needs, tailwater can be estimated by simply subtracting from IID's water deliveries the volumes of Colorado River water required for crop consumptive use, duck ponds, fish farms and salinity control (leaching), after adjusting for conveyance and distribution system losses and miscellaneous deliveries.

Using this approach, with IID's reinstated order at 3.1 MAF in total deliveries for 2003, tailwater is estimated to account for about 617 KAF, or about 25 percent of farm deliveries.

The volumes of tailwater and deep percolation in IID can also be estimated from detailed records for IID inflows and outflows. These records allow an accurate water balance for IID to be calculated on an annual basis, as has been done by Boyle (1993), by WST (1998), by NRCE (2002), and by Jensen and Walter (2002). Inflows to IID include those of the All-American Canal and the New and Alamo Rivers entering from Mexico, limited ground-water flow, and precipitation. Outflows include flows of the New and Alamo Rivers to the Salton Sea, diffuse flows and direct pumping to the sea, and evaporation from canals and drains. Relatively accurate measurements or estimates of flows internal to IID permit the partitioning of IID inflows into canal seepage and spillage, evapotranspiration, farm deliveries, and total farm losses. However, it is not possible to partition on-farm losses into the tailwater and deep percolation components using the district-wide water balance. Therefore, other techniques must be applied. These other techniques and their resulting estimates have varied widely (Scott, 2003a), and have included estimating or specifying the percentage of tail water and then predicting the percentage of deep percolation as a residual (this method was followed by IID, 2002), estimating deep percolation from a leaching requirement equation and then predicting the percentage of tailwater as a residual (this method was followed by Jensen and Walter, 2002), and comparing concentrations of conservative salts, such as chloride, in farm tile drains with surface water, and in some cases with final drain water to Salton Sea, to provide a quantification and reproducible estimate of the actual partitioning. This latter approach was applied here.

In fact, I applied two essentially independent conservative-constituent (chloride) balance approaches as a means to estimate the partitioning of farm losses into volumes of tailwater and deep percolation from the IID service area. One approach was that developed by Setmire et al. (1993, 1996) and previously used by him to estimate the fraction of the Alamo River composed of surface water (tailwater plus canal spillage) from chloride concentrations of the applied water, tilewater and Alamo River (or, in place of the Alamo River, surface drainage canal water tributary to the river). The knowledge of the total volume of drainage water from IID (sum of outflows to the Salton Sea, comprised of the sum of irrigation/drainage-related water, including spills, seepage, tailwater and deep percolation, M&I discharge flows and unconsumed rain), comes from the annual water balance of IID and is known with specified confidence (WST, 1998). The volumes of spill, seepage, M & I discharge flows and unconsumed rain waters are separated from the total volume of IID drainage water, and the residual is partitioned into the volumes of tailwater and deep percolation according to ratios of chloride concentrations.

The second model for partitioning on-farm losses into tailwater and deep percolation is a rootzone mass balance model that I used to estimate the fraction of infiltrated water in IID farms that emerges as net deep percolation. This model relies on knowledge of the chloride concentrations of the infiltrated water and tilewater. In turn, the volume of deep percolation is estimated in this approach from the above net deep percolation fraction and knowledge of the volume of water used in crop evapotranspiration. The volume of tailwater is determined, in turn, from the preceding volumes and the volume of water delivered to the farms. Annual volumes of tailwater and deep percolation were estimated using both methods with available data from the USGS and USBR regarding chloride concentrations and from the IID regarding water volumes, pertinent to the IID service area.

Each independent approach yielded similar estimates of tailwater and deep percolation volumes. These volumes are substantially different from those reported by IID (2002) to represent the IID-situation. The estimates of tailwater obtained by the chloride mass balance approaches are much greater than IID's estimates (about 637,400 acre-feet versus 386,000 acre-feet); correspondingly, the estimates of deep percolation obtained by the chloride mass balance approaches are considerably less than those reported by IID (2002) (about 165,400 acre-feet versus 417,000 acre-feet). Likewise, the resulting estimates of leaching fraction are different; they are about 0.09, based on the chloride mass balances, and 0.19 as reported by IID (2002). The estimates of tailwater percentage are also different; they are about 25% of farm deliveries, based on the chloride mass balances, and 15% of farm deliveries, as reported by IID (2002). The average chloride balance determined tailwater volume (637,000 AF) is within 3 percent of the independently calculated estimate of 617,000 AF (i.e., based on 3.1 MAF total diversion and current water need, as estimated earlier). In contrast, it is 65 percent greater or 251,000 AF greater than the tailwater volume purported by IID (386,000 AF). The mass balance approaches are concluded to be reliable approaches to use to resolve the contrasting estimates of leaching being achieved in the IID and of the volumes of tailwater being discharged to the Salton Sea.

Salt balance assessments based on salt concentrations of tilewater drainage in the IID strongly support the belief that there are physical limits on movement of water through soil profiles of IID on a district-wide basis. The apparent leaching fraction (LF) actually being achieved within IID, based on salt balances, appears to be no more than about 0.1, when expressed as a fraction of infiltrated water (Rhoades, 2003b), and is supported by physically constrained rates of vertical leaching in the heavier soils of IID as determined by Michel and Schroeder (1994). Data from the latter USGS study may be interpreted to conclude that the maximum amount of water that can be vertically percolated within the IID is about 135,000 (inferred from the USGS reported percolation rate, as explained in the next paragraph). The corresponding volume estimated from my chloride mass balance analysis is about 165,000 AF. Both of these independent estimates are far less than the 417 KAF suggested by IID (IID, 2002). That this limited level of vertical drainage has not caused undue salinity problems over the long-term for the vast majority of the district indicates that this physical constraint represents an advantage to the project efficiency. Thus, the volume of Colorado River water equivalent to ET plus that for leaching {[LR/(1-LR)](ET)} plus about 5-10 % extra water for compensation for non-uniformity and tailwater is a realistic goal for on-farm water delivery in the IID and probably represents about as much water as can be effectively infiltrated into the soils on a district-wide average, with small amounts of accidental tailwater runoff.

The relative "tightness" of heavy soils in IID, following the filling of cracks by water during irrigation, tends to beneficially increase uniformity of irrigation. This conclusion is clearly demonstrated by the data of Mitchell and van Genuchten, 1993, Grismer, 2003 and Michel and Schroeder (1994). The estimate of a 9 cm per year average vertical percolation rate for IID soils made by Michel and Schroeder (1994) may be used to estimate the attainable leaching fraction, deep percolation volume and tailwater volume. These values are about 0.06, about 135,000 acre-feet and about 668,000 acre-feet, respectively, assuming an annual farmed acreage of 450,000 acres and total drainage volume of 803,000 acre-feet (the latter value taken from IID, 2002). The estimate of the IID-wide tailwater volume of about 165,000 acre-feet and F_n factor of about 0.97 from the chloride mass balance results determined herein is fully consistent with the conclusion that the low permeability of the IID soils limits deep percolation rates. The leaching and on-farm irrigation water requirements determined for the IID district-wide situation are in keeping with this relatively low attainable leaching fraction and the relatively high F_n value of 0.95 used herein. The provision of much more additional water for leaching and non-uniformity compensation than that specified would likely only result in more tailwater and accompanying soil aeration, scalding and water logging problems, with little benefit to soil salinity reduction. These independent estimates made using the USGS data support those obtained by means of the chloride balance analysis.

Procedures and Results

The procedures, data and results that I determined, along with the logic and basic relations and approaches, for each of the above four objectives stated at the beginning of this memorandum are presented in abbreviated form herein. More detailed information is given in the two special reports that I have provided to MWD (Rhoades, 2003a and 2003b). The references cited herein are mostly listed in the latter Report; the others are given in the references list placed at the end of this report. In these Reports are also given derivations of a number of relations and equations that I developed (others are found in Rhoades, 2002) and used in the determinations made herein, including those used to account for the effect of horizontal-leaching and tailwater drainage on the leaching requirement, those used to compensate for the effect of non-uniformity and inefficiency of irrigation in the calculation of the on-farm irrigation requirement, with consideration of beneficial water use, and those used to assess the volumes of tailwater and deep percolation from irrigation of the IID service area. Detailed tables of example results that were obtained using the LR-related equations to calculate irrigation and drainage water requirements are provided in these Reports, as are examples of the calculation procedures and the results of a sensitivity analysis of the underlying relationships. The purpose of the sensitivity analysis was to determine the relative effects of the various involved parameters upon the leaching and water requirement values and the amounts of beneficial water use, according to my logic and approach. Because these derivations, data and examples are too extensive and detailed for this memorandum (the data and results are contained in hundreds of tables and figures), I refer you to these Reports for the more detailed technical and scientific explanations, descriptions of procedures, data, results, discussions, and conclusions, as well as full documentation of my undertakings on behalf of MWD in this matter. The tables and figures provided herein are taken from the latter Reports and, hence, the numbers are the same as given there, for sake of consistency.

The LR value is the net fraction of infiltrated water that must pass through the rootzone over time in order to keep the level of soil salinity in the active rootzone within acceptable limits for full-potential crop production, assuming uniform conditions of water application, infiltration and leaching within the field and, traditionally, the absence of any significant removal of previously accumulated infiltrated salts by the processes of horizontal-leaching and tailwater runoff. Thus, the LR is usually referenced to the amount of infiltrated water (V_{infw}). However, it can be modified to account for horizontal-leaching and/or tailwater runoff and it can, alternatively, be referenced to the amount of water applied to the field (V_{iw}). I use V_{infw} as my reference for LR herein; relations are provided later for converting between these two alternative water-references. I use the modified LR assessment procedure described in my comprehensive Report (Rhoades, 2003a) to account for the amount of salt removed from the soil by horizontal leaching and tailwater runoff. I adjust for irrigation distribution non-uniformity and inefficiency, when I use the LR data to calculate irrigation requirements, using the relations described and demonstrated in the latter Report.

For year 2003 conditions, I estimated the leaching requirement for the IID-wide service area, taking into account the salinity composition and concentration of the irrigation water (Colorado River), the mixture of crops grown in the IID and consumptive-use requirements corresponding to the average data of 2000-2002 and available standard crop salt-tolerance data. The LR value provided is the overall "consumptive-use and leaching requirement" weighted District-wide LR, termed LR_{infw}, and is referenced to the volume of infiltrated water. The LR_{infw} represents the requirement for the mixture of crops presently grown in IID. The following describes the data and basic procedure that I used.

The crop consumptive use (ET) data that I used in all of my calculations were those provided by Dr. R. G. Allen (Allen, 2003b). The methodology that he used to determine these data is described elsewhere (WST, 1998; Allen, 2003b). The preliminary consumptive use data used to determine the leaching requirement are summarized in Table 1c (Rhoades, 2003a). The total consumptive use volumes that were subsequently revised and used to calculate the water requirements are also given in Table 1c. These calculations of crop ET are likely to be more accurate than those by other entities. They considered and include the following components that impact the magnitude and reliability of ET calculations, as described by Allen (2003b):

1. Quality control analysis and correction of CIMIS weather data. Allen (2003b) tested and corrected solar radiation, humidity and precipitation data from the three CIMIS stations in IID for their periods of record and recomputed reference evapotranspiration (ET_o).

2. Correction of the net radiation bias in the CIMIS ET_o record. The re-computation of ET_o by Allen (2003b) for the three CIMIS weather stations in IID eliminated any time-based bias in the reported CIMIS ET_o data record caused by conversion from measured net radiation to calculated net radiation in the CIMIS program and

potentially faulty net radiation calculations in the CIMIS data routines since the conversion.

3. Application of the dual crop coefficient (K_c) procedure of FAO-56 for calculating evapotranspiration (ET_c) from crops. The dual K_c procedure was applied by the Water Study Team (WST, 1998) for 1989-1996 and extended by Allen (2003b). The dual K_c procedure separately predicts evaporation from the soil surface from basal evapotranspiration, thereby producing calculations of ET_c that accurately reflect the impact of frequency of irrigations on total amount of ET. The dual K_c procedure of FAO-56 was computed daily and adhered to the law of conservation of mass, where evaporation of water from soil is limited by capacity of the upper soil layer and by the total input of irrigation and rainfall per wetting event. Allen (2003b) established mean crop coefficients for the IID crops that incorporate the impacts of wetting frequency on the mean K_c value.

4. The use of the dual K_c procedure provides the ability to establish the amount of precipitation that is effective in reducing the ET demand for irrigation water. Allen (2003b), using data from the WST (1998) report, established the effective component of precipitation in IID to be only 34% of total precipitation, on average. Over 50% of precipitation in IID evaporates from soil surfaces following rain events and is therefore not useful in reducing the ET demand for irrigation water.

5. The WST (1998) K_c values utilized by Allen (2003b) were calibrated by WST using ET from IID measured using a district-wide inflow-outflow water balance for the period 1990-1996. The reduction in K_c values during calibration averaged 8% across all crops, with forage crops having greater adjustment than vegetable crops (WST, 1998). The proportional distribution of the reduction was made across all crops according to a grid-pattern of visual assessment of crop growth and vigor obtained from high-resolution aerial photos (WST, 1998).

6. The crop coefficient curves by the WST (1998) and used by Allen (2003b) were applied using mean planting dates by crop that were specific to each year. These dates were assembled by WST (1998) from monthly crop acreage summaries.

7. WST (1998) used monthly crop acreages reported for forage crops (alfalfa, Sudan, Bermuda, pasture) to compute ET by month. This reduced the biases that would occur in ET calculations that rely on annual acreage values produced by averaging across all months of a year. The bias occurs because of large changes and trends in acreages for forage crops from month to month. Use of an annual average across all months causes an over-prediction of annual ET by alfalfa, for example, due to typically reduced acreage of alfalfa during summer. In addition, as described by Gabrielsen (2003), WST (1998) and Allen (2003b) applied more correct estimates of acreages for annual crops in the ET calculations as compared to the process used by IID in preparing their annual acreage summaries.

8. The annual ET calculated by Allen (2003b) for years 1997-2002 for IID crops include the seven considerations described above and therefore represent accurate estimates of actual ET of Colorado River water from IID farms.

9. The WST calibration of K_c ET_o to the water balance was applied to all crops, in part, with forage and other low value crops being assessed a larger reduction. This contrasts with the approach of Jensen-Walter, 2002; they reduced the ET of alfalfa, only. It is common practice within IID, when farm water demands exceed system capacity, to delay delivery of water to low value crops by one day, in order to shave peaks. Thus, one would expect that numerous crops besides alfalfa could suffer from some water stress. In addition, all crops have some probability of having planting skips, cultivation accidents, etc. that would reduce the ET.

10. For many crops, including alfalfa, Jensen-Walter apparently used the same annual acreage values as reported by IID. The WST (1998) and Gabrielsen (2003) showed that the IID annual acreage values for alfalfa and many winter crops, especially, are in error. Therefore, the WST and MWD ET values are more dependable because of their basis on more accurate acreage. Differences in acreages for alfalfa between those by WST and Gabrielsen and those by IID <u>and</u> Jensen-Walter (2002) can be as great as 20,000 acres (see Allen, 2003b). These differences are caused by the IID practice (apparently accepted by Jensen-Walter) to select the maximum reported monthly acreage within a calendar year as representing the alfalfa acreage for the year. WST and Gabrielsen averaged alfalfa acreage over the year. The IID practice will cause over estimation of highest ET since alfalfa acreage tends to be at its lowest during summer months when ET is highest. The WST practice produces more representative annual ET estimates. In addition, WST (1998) applied monthly acreages of alfalfa separately to each month to more correctly sum the annual ET from alfalfa.

11. The $K_{c\ mean}$ crop coefficients used by Jensen-Walter performed well against the water balance derived ET during the wetter period of 1989-1999. However, the 2000-2002 period has been one of very low precipitation, with consequently less evaporation from soil. Therefore, the $K_{c\ mean}$ values of Jensen-Walter will tend to over-predict total ET from IID. This may explain why Jensen-Walter over-predicted ET as determined by water balance for 2000 and 2001.

The leaching requirement values based on the earlier data are equally valid for the later data, because the changes in consumptive use are proportionately the same for all crops. Mean values and confidence intervals for the three-year period (2000-2002) are assumed to be applicable to the year 2003. The estimate of the mean net crop ET requirement of Colorado River water (excluding effective rainfall), based on the three-year average, is 1,705,289 +/- about 14,600 acre-feet, for the estimated prevailing mix of crops. Additional water of about 28,500 acre-feet is required for the duck ponds and fish farms in IID. The crop consumptive use requirements for river water are based on a detailed calculation of requirements for specific crops that included separate calculation of evaporation from soil conducted on a daily time-step using reference ET and crop coefficients. The method and results were calibrated to ET as determined by the water balance of IID by the WST (1998). Crop consumptive used calculated by this procedure is considered to be dependable and accurate since it includes estimates of evaporation from rainfall that vary each year.

The average salinity and composition of the Colorado River water used for estimating the current leaching requirement is the average from 2000-2002 (see Table 2; Rhoades, 2003a). These data were developed from bi-weekly samples collected above Imperial Dam and analyzed by the USBR Yuma Desalting Plant Laboratory. The average salinity for 2000-2002 and predicted for 2003 is 1.091 dS/m, which is lower than it was during 1989-1996 period, when it averaged 1.213 dS/m.

The above-described data were used to calculate the leaching requirement of the IID for estimated year 2003 conditions. The LR_{infw} value for each significant crop grown in the IID was determined using the most recent tabulation of crop salt-tolerance (Maas and Grattan, 1999) and the WATSUIT leaching requirement model (Rhoades, et al., 1992) (termed here as LR_W). The LR_W determination accounts for any removal of soluble salt within the crop rootzone by the precipitation of insoluble salt-minerals (calcite and gypsum). The loss of salt by mineral precipitation is appreciable for Colorado River water and reduces the need for leaching, especially at low leaching fractions (Rhoades et al., 1973, 1974; Oster and Rhoades, 1990). The relatively simple steady-state WATSUIT model was used because it has been demonstrated to provide essentially the same results as the more rigorous process-based transient UNSATCHEM model. The UNSATCHEM model is not practical to use for determining district-wide LR because of the large data requirement, including detailed knowledge of crop rotations and irrigation frequencies and amounts (Rhoades, 2002). The leaching requirement (LR_{infw}) was also determined using the so-called Traditional model (Rhoades, 1974) (termed here as LR_T). The LR_T model does not account for salt removal by mineral precipitation in the soil and is therefore, not as accurate a model to use within IID. However, LR_T was calculated and provided for the sake of comparison.

The overall IID-wide value of LR_{infw} was determined by dividing the total volume of leaching water required for all cropped acreage by the total volume of water required to be infiltrated into the rootzones for all crops. This calculation considers the acreage planted to each crop as well as the volume of infiltration and evapotranspiration for each crop and individual crop sensitivity to salinity. The means undertaken to make these calculations and the results are given in Table 3i (Rhoades, 2003a). The ET data used in this table have been revised, as shown in Table 1c, but the LR values determined in this table are still correct, since the revised ET values apply uniformly proportional for all crops.

The value of LR_W determined for the 2003 IID-wide situation is 0.06 (+/- ~0.003), assuming the salinity of the Colorado River water used for irrigation is 1.091 dS/m and the composition of the Colorado River is the same as the average of the last three years (see Rhoades, 2003a) and assuming that the crops being grown and their proportional use of the total crop consumptive use requirement are those given in Table 1c (Rhoades, 2003a).

The above-described values of leaching requirement do not include adjustment for the effects of horizontal leaching and tailwater runoff, nor non-uniformity effects. The latter matter will be discussed later. The effect and benefit of horizontal leaching was considered in detailed scientific assessments. Explicit, correct equations were developed to include the combined effect of horizontal-leaching and tailwater runoff on the determination of the leaching requirement (Rhoades, 2002 and Rhoades, 2003a). These equations will not be discussed here but are given in Table 4a (Rhoades, 2003a), along with corresponding equations to calculate volumes of required water for application, infiltration and leaching and to assess total water requirements. The definitions of the symbols used in these equations are given in Table 4b (Rhoades, 2003a). The amount of salt removed by tailwater increases with the volume of tailwater, but the process is very inefficient, and not to be recommended for this reason and others. The second equation listed in Table 4a (Rhoades, 2003a) describes the effect of horizontal leaching on LR_{infw}. The equation used to calculate the beneficial volume of tailwater (BV_{tw}) is also given in Table 4a (Rhoades, 2003a).

Many examples are given in the two preceding Reports to show that horizontal leaching contributes very little to required leaching for soil salinity control. Data are presented herein, as well, which demonstrate this conclusion. They are contained within Table 13a (Rhoades, 2003a), which lists the determined volumes of required Colorado River water for on-farm deliveries in 2003, among other information. Data provided in this table show that LR_W is reduced from about 0.058 to about 0.056 by horizontal leaching, when the tailwater percentage is 15% of farm deliveries. The percentage of the tailwater that contributes beneficially, in this regard, is only about 1 percent (3.7/335.6); the corresponding IID-wide volume is 3,700 acre-feet at a tailwater percentage of 15 percent (IID's regulated limit).

Though the effects of horizontal leaching and tailwater runoff on the leaching requirement and associated water requirements are so small that they could justifiably be ignored, as shown above, they are included in all of the following determinations of on-farm water requirements for the sake of scientific completeness.

Determination of IID's On-Farm Requirement for Colorado River Water

The proper assessment of on-farm water needs within IID requires detailed calculations and models to account for gains and losses of salinity and salt concentrations within the crop rootzone. These calculations and models are necessary to account for such factors as the concentrations of salt that occur in the soil solution, the amounts of salts dissolved from the near-surface soil by horizontal-leaching, the amount of applied salt that precipitates from solution in the soil matrix of the rootzone (and no longer can impact plant growth), and the amount of salt discharged in the tilewater. A proper analysis must also account for differences that occur in these factors from one irrigation to another as the crop season progresses, from one crop to another throughout the crop-rotation, and in between crops, such as when the land is pre-irrigated. It also must account for site-specific factors and influences, such as the cracking-type clay soils which occur on part of the IID lands.

In my analysis, I used the WATSUIT computer model, incorporating some recent refinements and additions that I developed to include and integrate vertical-leaching processes with the effect of horizontal-leaching for the cracking clay soils of the IID, as explained earlier. My analysis of the on-farm irrigation requirement also considered the following factors:

- the amount of water lost from the farm due to crop ET;
- the actual acreages and respective ET of the crops grown in IID,
- the total dissolved salt concentration and constituent composition of the irrigation water,
- the vertical-leaching requirement (expressed as the fraction of the applied water that infiltrates the soil that must be discharged as deep percolation (tilewater) in order to keep the salinity level within acceptable levels for full crop production),
- the salt tolerances of the various crops grown in IID,
- the amount of tailwater allowed to be discharged from the fields,
- the amount of soil salinity removed by the tailwater by so-called horizontal-leaching,
- the physical properties of the soils that affect their infiltration rates and capacities,
- the average effective rainfall for the IID, and the uniformity and the field irrigation efficiency of the prevalent irrigation management.

Some discussion of the effects of non-uniformity of irrigation application, infiltration and leaching is required before I present the volume of Colorado River that was determined to be required in IID to meet the needs of crop consumptive use and leaching (recognized beneficial uses of Colorado River water). This is because, allowance was provided for additional water to compensate for such effects. Most of the details in this regard are provided elsewhere (Walker, 2003a-d; Allen; 2003a and in my comprehensive Report, Rhoades, 2003a). The following discussion provides the general basis and procedure for calculating the non-uniformity allowance.

A. Compensation for Irrigation Non-Uniformity and Inefficiency

Uniformity of water application-infiltration-leaching was assumed (as is the convention) in the above-described determinations of the leaching requirement. However, complete uniformity of leaching (or of irrigation application and infiltration) is not usually achieved in actual cropping and irrigation operations. The combined effect of non-uniformity of water application, infiltration and leaching often results in relative distributions of deep percolation like that illustrated in Figure 2 (Rhoades, 2003a). As indicated, some excess deep percolation may occur at the head end of the field while some under application and infiltration may occur at the tail end. Additionally, in this figure, the various potential ultimate destinations of the total volume of applied water are schematically represented.

If the irrigation water could be applied completely uniformly to a uniform soil (infiltration rate) and unstressed uniform crop, only a volume of irrigation water equivalent to the potential crop consumptive use plus the required leaching would need to be applied and infiltrated. But often with surface irrigation systems, non-uniformity of irrigation results in excess irrigation water being infiltrated toward the upper-end of the field (because the opportunity time for infiltration and the average water-depth are greater there) and in insufficient water being infiltrated toward the lower end of the field (because the opportunity time and the average water-depth are less there). In such typical cases of non-uniformity of application and infiltration, the actual volume of water utilized in crop ET is usually slightly less than maximum-potential crop ET and the actual volume of deep percolation effectively used in leaching is usually less than that theoretically required.

To minimize these unattained amounts of required beneficial crop ET and "leaching", additional water is sometimes intentionally applied as a means to compensate for the non-uniformity induced un-attainment. With such increased application: 1) the volume of applied water exceeds the amount required to be infiltrated, 2) the volume of excess deep percolation will increase, especially in the upper part of the field, and will leach out more salt than is actually necessary and, hence, add unnecessarily to the total drainage requirement, often creating water table problems (crop yield reduction caused by insufficiency of aeration and subsequent increase in soil salinity from upward flow), 3) the total volume of deep percolation exceeds the required deep percolation and 4) if tailwater is allowed, a fraction of the applied water runs off the field without being infiltrated, thus not contributing to either ET or appreciably to the leaching requirement (as was shown earlier), while unnecessarily increasing the surface drainage requirement. The relative amount of each of the above-described destinations varies with the amount of tailwater, and with the shape of the application-infiltration-deep percolation curve, which in turn vary with irrigation management (advance rate, recession time, etc.) and soil intake properties. In any case, for a non-uniform situation, the effectively irrigated and leached portion of a field is usually slightly less than the total field area and total deep percolation is usually greater than the theoretical required deep percolation. It is noted that adjustment in the theoretical leaching requirement calculation is not typical and thus such adjustment here represents an appropriate but more conservative estimate than would be obtained by previously utilized methods.

Allen (2003a) provided target values for leaching effectiveness and sufficiency that appropriately minimized reductions in ET and yield and excessive deep percolation losses. This information was used to determine the appropriate value for the "non-uniformity/inefficiency compensation factor" (F_n). F_n is equivalent to the so-called distribution efficiency (Allen, 2003a), and accounts for incidental deep percolation of water in excess of that required for ET and leaching. The value for F_n is a function of the distribution uniformity (DU) of irrigation infiltration for the irrigation system and the adequacy of each irrigation event in fulfilling the water requirement for the field. A value $F_n = 1$ indicates perfect uniformity. Allen (2003a) determined $F_n = 0.95$ to be appropriate for irrigation systems in IID, based on a DU = 0.85 and simulation results by

Walker (2003a,b), for high levels of irrigation adequacy necessary for high levels of crop production.

For non-uniform conditions, introduction of F_n compensates for non-uniformity when calculating the on-farm irrigation delivery requirement (RV_{iw}) by increasing the volume of water to be infiltrated (and applied) relative to the requirement that is based on perfect uniformity of crop ET (V_{et}) and LR_{infw} within the field as follows:

$$RV_{iw} = \{(V_{et})/[(1-LR_{infw})(F_n)]\}/(1-F_{tw}), \qquad [1]$$

where F_{tw} is the fraction of field delivery that is tailwater. Equation (1), with and without inclusion of LR_{infw}, and other equations given in Table 4a (Rhoades, 2003a) were used to calculate volumes of deep percolation as a function of the tailwater fraction (F_{tw}) and the distribution inefficiency factor (F_n), for a normalized situation where crop consumptive use is set equal to 100. These results are given in Table 6 (Rhoades, 2003a). These results show that the application of excess irrigation water provided to compensate for non-uniformity and inefficiency of application-infiltration-leaching can result in deep percolation amounts that substantially exceed the required amounts of deep percolation for leaching (RV_{dw}), especially when F_n values are less than about 0.90. As mentioned earlier, such excessive volumes of applied water, if not simply lost as increased tailwater, may have serious consequences, including elevated water tables and drainage requirements and their associated costs (both on-site and off-site costs). The effects of non-uniformity compensation and the consideration of both beneficial and non-beneficial impacts and costs should be considered when selecting the value of F_n. The selection of an F_n without considering the consequences and costs of excessive deep percolation will result in the selection of inappropriately low F_n values, because such selection is focused on the achievement of high uniformity of water application and infiltration, as thought needed for ET and LR purposes only. The negative benefits of "over-irrigation" should be considered in economic evaluations of non-uniformity/inefficiency compensation, in addition to the positive benefits of increased crop yield. These results also demonstrate that for values of F_n less than 0.95, it is not necessary to include LR in the inefficiency compensation process because deep percolation associated with the irrigation water requirement based only upon ET can provide enough excess water under low F_n to meet the beneficial vertical-leaching requirement over most of the field. In addition, physical percolation constraints of many of the IID soils preclude the use of both LR and low F_n values, because this consideration requires deep percolation amounts that are greater than those physically possible (Michel and Schroeder, 1994, Walker, 2003a, 2003b).

It is also inappropriate to provide appreciable extra water for non-uniformity compensation when excessive tailwater is being employed. If tailwater is being justified for increasing uniformity, then the value of F_n should be adjusted upward accordingly. Otherwise, excessive non-beneficial water will be provided using Equation [1] in a kind of double accounting, as demonstrated in Table 6 (Rhoades, 2003a). The selection of the value for F_n needs to consider the feasibility of reducing some of the current tailwater runoff and utilizing this water to enhance the volume and uniformity of infiltration in order to conserve total water consumption. Thus, the total volume of non-beneficial water needs to be considered in the selection of the F_n value, giving consideration to the tailwater fraction.

The practical ability to achieve various levels of distribution efficiency for IID conditions of soils and various optional methods of irrigation management was evaluated by Dr. W. R. Walker using the infiltration model and methods that he developed (Walker, 2003c). Based on findings by Dr. Walker, the proper value for F_n in Equation [1] to provide sufficient adequacy of irrigation to account for non-uniformity was further evaluated by Dr. R. G. Allen (Allen, 2003a) and Mr. Harold Payne (Payne and Brown, 2003). The models applied by Drs. Walker and Allen offer the advantage of providing information that can be directly used to design and manage irrigation systems as needed to meet the determined required values of F_n. These methods were used to help select appropriate values of F_n, with consideration being given to crop yield reductions and the economic losses caused by insufficiency of applied water and of salinity leaching, as well as by the economic losses caused by excesses of applied water, leaching, aeration and water logging problems and increased drainage requirements (Payne and Brown, 2003).

It was concluded that the IID situation is very conducive to the achievement of uniform water infiltration and leaching because the cracking soils allow for a rapid filling of void space followed by a rapid decline in infiltration rate to very low levels (Grismer, 2003). Thus, the need for additional water for irrigation non-uniformity and irrigation inefficiency is minimal for such soils. It is my opinion based on the data cited earlier that one can hardly achieve much more leaching than that presently being achieved in such soils; increasing tailwater will not enhance uniformity much nor will it significantly increase leaching, but it will add to the potential to increase "ponding and scalding" problems associated with excessive water buildup in the tail-end sections of such fields (as shown by surface irrigation simulations and field observations). It was concluded by the MWD team that a conservative estimate of the extra water required to compensate for non-uniformity considerations in the IID is equivalent to that obtained by dividing the water duty associated with homogeneous conditions of both crop ET and LR by a factor (F_n) of 0.95 when tailwater percentages are 15 percent and less. In my opinion this is liberal for tailwater percentages greater than about 10 percent and amounts to some degree of double accounting. Since the water that is lost in tailwater does not provide significant beneficial use in soil salinity control or in achieving uniformity of irrigation and leaching, it should be minimized; a F_n factor of 0.95 is appropriate for calculations aimed at IID's optimal requirements.

The selection of the value of $F_n = 0.95$ and achievable tailwater fraction of 0.05 as target values for IID are supported by the observations that: 1) Bali and Grismer have successfully demonstrated that alfalfa and Sudan can be successfully produced in high clay content soils of the IID with tailwater runoff less than 5 percent using simple "reduced-runoff" irrigation systems (Grismer, 2003), 2) alfalfa, wheat, sugar beets and cantaloupes have been successfully grown in high clay content soil in the IID without any tailwater runoff using level basin irrigation and under conditions of abnormally high levels of irrigation water salinity (Rhoades, et al., 1988), 3) Boyle Engineering (1993) concluded that it was practical to reduce tailwater to about 5 percent using tailwater recovery systems, 4) Dr. Wynn Walker concluded from his surface-irrigation simulations that it was practical to achieve 95 percent irrigation infiltration uniformity in the high clay content IID soils using blocked end irrigation systems (Walker, 2003a, 2003b), 5) Harold Payne concluded from his field observations and evaluations of the IID situation and Arizona experience that it was practical to reduce tailwater to 5 percent with only management changes and relatively inexpensive systems changes (Payne and Brown, 2003), 6) the leaching fraction being achieved in the IID over the 1989-96 period was only about 0.09 (Rhoades, 2003b) and crop yields appear to be good and stable at this level of leaching (Gabrielsen, 2003) and 7) the results of the chloride mass balance assessment presented later in this report suggest that the low permeability of the IID soils may impose a limit on F_n to a value of no less than about 0.95.

B. Calculation of IID's 2003 On-Farm Requirement for Colorado River Water

As previously discussed, the estimation of the irrigation water duty in the IID requires appropriate information on the crop water requirement (V_{et}), the effective rainfall (V_{rw}), the leaching requirement (LR_{infw}), the value of F_{ctw} (if horizontal leaching occurs and tailwater is allowed), the salinity of the irrigation water, the salinity-tolerances of the crops grown, the need to compensate for irrigation distribution inefficiency, which varies depending upon irrigation management, and the amount of non-beneficial water determined to be reasonable.

With these factors in mind, I estimated the on-farm water-duty using the relations for the required volume of irrigation water (RV_{iw}) given in Table 4a (Rhoades, 2003a), for the estimated prevailing combination of net crop consumptive use (in excess of that provided by effective rainfall) and leaching requirement (including the benefit of horizontal leaching, assuming the F_{ctw} factor is 1.19 for the IID-wide situation), as described earlier, using the value of 0.95 for F_n and three levels of tailwater percentage deemed appropriate for analysis by the MWD team (considering present and future potential conditions). The three levels of tailwater were selected to permit the estimation of the water requirement of the IID service area that can be immediately achieved in 2003 by simply holding irrigators to a cap of 15 percent tailwater according to current IID regulations (this irrigation water requirement is termed 15% _F_n = 0.95), as well as the water requirement given the implementation of relatively simple inexpensive management practices (Payne and Brown, 2003 and Walker, 2003a, 2003b) that can further reduce F_{tw} to 10% (this water requirement is termed 10%_0.95) and, with additional time and with somewhat more costly but still practical improvements, reduce tailwater to 5 percent (this water requirement is termed 5%_0.95). These three requirements assume the salinity of the Colorado River, crop ET and effective rainfall values are constant into 2003. Most of these results are summarized given in Table 13a (Rhoades, 2003a). The data for LR_T are given for sake of comparison. The effects of differences in rainfall, crop ET and Colorado River salinity and other details are described in my more comprehensive Report (Rhoades, 2003a).

The volume of Colorado River water required for delivery to farms in IID to meet all irrigation requirements for 2003 year conditions (excluding duck ponds and fish farms) without any reduction in crop acreage or yield is determined to be 2238 KAF +/- about 48 KAF, provided tailwater runoff is capped at 15 percent as specified in IID regulation. The 95% confidence interval (48 KAF) was estimated as being twice the range observed in annual requirements for the preceding three-year period 2000-2002, because three years of data are insufficient to calculate a reliable standard deviation value (the calculated SD value was about 24 KAF). The requirement for Colorado River water is increased by about 28,000 acre-feet to meet the additional needs of duck ponds and fish farms. The volume of tailwater corresponding to this case is 336 KAF. The farm delivery requirements for Colorado River water in IID to meet on-farm cropping needs are reduced to about 2115 KAF and to about 2005 KAF as practical management is implemented in the near term to reduce tailwater to 10 percent and 5 percent, respectively. The farm delivery requirement can be reduced even more with the implementation of more costly and time-consuming structural improvements. The volumes of tailwater corresponding to the 10 and 5 percent tailwater conditions are 2112 and 100 KAF, respectively. The volumes of tailwater under prevailing conditions in the IID are estimated and discussed in the next section.

The above estimates for the 2003 IID on-farm water duty is believed to be conservative for the following reasons:

1. Salt tolerance threshold values used in the analyses are conservative (on the low side) causing leaching requirement (LR) calculations to be conservatively high. As an example, the varieties of alfalfa now grown in the IID are more salt tolerant than those grown in the 1960's and upon which the listed value of 2.0 dS/m is based (based on conversations I had with Drs. C. Grieve and S. R. Grattan, recognized crop salt-tolerance specialists of the US Salinity Laboratory and University of California, respectively). The salinity tolerance of current varieties is likely significantly higher. Furthermore, the salt tolerance values are generally conservative because the threshold values typically are mathematically derived values of the salinity level at which an initiation of growth reduction due to soil salinity just begin, but which can't be discerned or accurately measured experimentally even under the best field test conditions. Thus, the threshold values used are conservative.

2. It is believed that most of the deep percolation in IID contributes to required leaching. This is because the IID-wide leaching fraction (LF) is low (about 0.09; see Rhoades, 2003b) and so many of the soils have low permeability. This conclusion is supported by the data and reasoning that I provided earlier in this treatise and by other found in other references (for example, Ayers and Wescot, 1985; Mitchell and van Genuchten, 1993). For a typical irrigation of fine-textured soils, distribution of infiltration is high, and thus, deep percolation has high uniformity and can be credited towards fulfilling leaching requirements. For typical irrigation on coarser-textured soils, the relatively large amounts of incidental deep percolation caused by non-uniformity of infiltration are sufficient to satisfy all leaching requirements over more than 90% of field areas (Allen, 2003a). This excess deep percolation likely flows to lower lying fields within IID,

where some of it is subsequently consumed by deep-rooted crops. Thus, the low LR of IID is met by low amounts of relatively uniform deep percolation on fine-textured soils and by relatively larger amounts of less uniform deep percolation on coarse-textured soils that are subsequently partially recaptured and used elsewhere in the District.

3. Multiple irrigations have higher uniformity of infiltration than do individual events (Allen, 2003a). Many portions of a field that are under-irrigated during a single irrigation event tend to have higher than average infiltration rates for a subsequent irrigation event (because they are more cracked and drier). The resulting relatively higher infiltration rates encourage relatively greater infiltration depths for those areas during subsequent irrigation event(s), thereby resulting in more uniform infiltration across multiple events. As discussed in item 7 below, river basin-scale salt balances on IID (Alamo River basin) indicate that net season-average irrigation uniformity within IID is high, due to physical constraints by soils.

4. Many fields in IID are prone to having a shallow water table develop during parts of the growing season and following large irrigation events. This shallow water can supply a portion of the ET requirement of medium and deep-rooted crops (Grismer, 2003). Therefore, some of the deep percolation losses computed by simulation models or as observed during field studies actually contribute beneficially to the overall ET requirement.

5. Because the soil profile has large capacity to accumulate salts, some build up of salts during irrigation events having low amounts of leaching can be tolerated over the short term, for example, over a single growing season. The required leaching is subsequently provided during pre-plant and early season irrigations, especially after the soil has been dried and tilled following the harvest of the previous crop (Rhoades, 2002).

6. The leaching achieved is actually higher than that indicated in this analysis because of the extra water given for "compensation" ($F_n = 0.95$). The effective leaching fraction is about 0.11 when effects of deep percolation from non-uniformity are considered (as can be determined from Table 13a (196.6/1806.8). The leaching will be increased as tailwater is captured and utilized within the field, such as by using blocked ends (Walker, 2003a). For example, if the volume of water equivalent to a tailwater of 5 percent is diverted to deep percolation, it increases the field-wide leaching fraction from 0.1 to 0.145; thus the corresponding reduction of average soil salinity is substantial.

7. Salt balance assessments based on salt concentrations of tilewater drainage and isotopic analyses of percolation rates (Michel and Schroeder, 1994) in the IID strongly support the belief that there are physical limits on movement of water through soil profiles of IID on a district-wide basis. The apparent leaching fraction (LF) actually being achieved within IID, based on salt balances, appears

to be no more than about 0.1, when expressed as a fraction of infiltrated water (Rhoades, 2003b). The results of the chloride mass balance data presented later show that the value of F_n is likely limited by the low permeability soils to a value of no less than about 0.95. That this level has not caused undue salinity problems over the long-term for the vast majority of the district indicates that this physical constraint represents an advantage to the project efficiency. Thus, the volume of Colorado River water equivalent to ET plus that for leaching {[LR/(1-LR)](ET)} plus about 5-10 % extra water for compensation for non-uniformity and tailwater is a realistic goal for on-farm water delivery in the IID and probably represents about as much water as can be effectively infiltrated into the soils on a district-wide average, with small amounts of accidental tailwater runoff.

8. The relative "tightness" of heavy soils in IID, following the filling of cracks by water during irrigation, tends to beneficially increase uniformity of irrigation. This conclusion is clearly demonstrated by the data of Mitchell and van Genuchten, 1993 and Grismer, 2003. The leaching requirements estimated for the IID-wide situation are in keeping with this relatively low attainable leaching fraction. The provision of much more additional water for leaching than that specified would likely only result in more tailwater and in more soil aeration, scalding and water logging problems, with little benefit to beneficial soil salinity reduction.

The volumes of Colorado River water required for diversion into IID, including the on-farm irrigation requirements described above for 2003 (Table 13a) are given in Table 15. Also given in this table are the additional volumes of Colorado River water required for duck ponds, fish-farms, miscellaneous deliveries and conveyance/distributions upstream of the farm headgate (net diversion requirement), including adjustment for estimated return flow credit (estimated return flow credit), along with the corresponding volumes for the Reinstated Order (as reported by Scott, 2003b). The total of these volumes gives the MWD-team estimates of the "Diversion Requirement" of Colorado River Water for each of the tailwater cases considered, in comparison to the Reinstated Order. After adjustment for return flows, the differences between the Reinstated Order and those for the three estimates equals the volumes of tailwater loss that can be conserved in IID, if not more. In terms of reduced diversions, these volumes are 291,317 (15% tailwater), 417,909 (10% tailwater) and 531,445 (5% tailwater) acre-feet, including additional water allotted for irrigation non-uniformity considerations.

Estimation of Volumes of Tailwater and Deep Percolation in IID

Losses of water occur on-farm within the Imperial Irrigation District (IID) service area in the form of tailwater and as excess, but limited, deep percolation. Deep percolation is required for the control of soil salinity; whereas, tailwater contributes only a very minor, insignificant amount to salinity control (in my opinion it likely contributes more to soil salinization problems than it reduces them). Additional losses of water occur in the IID service area by spillage and by seepage from the delivery canals. It is of interest to determine the volumes of each of these loss components. The greatest interest, controversy and uncertainty involve the relative proportion and volumes of tailwater and deep percolation.

Based on the required volume of Colorado River water for on-farm irrigation calculated using WATSUIT, tailwater can be estimated by simply subtracting this amount from IID's water deliveries, after adjusting for conveyance and distribution system losses, miscellaneous deliveries, and return flows. Using this approach, with IID's reinstated order of 3.1 MAF in total deliveries for 2003, tailwater is estimated to account for 617,000 AF, or about 24.5 percent of farm deliveries (Scott, 2003b). This assumes that deep percolation is physically limited to the amount required for leaching plus the additional allowance for distribution non-uniformity, and thus as calculated directly from WATSUIT, accounts for about 196,600 AF.

Mass balance calculations involving conservative dissolved constituents (solutes such as chloride) offer another tool to estimate the volumes of tailwater and deep percolation. In this section, I describe the application of several approaches based on mass balance concepts utilizing chloride concentrations to estimate the on-farm volumes of deep percolation and tailwater. The logic, assumptions and methods used to make these estimates are described and examples are given to demonstrate the calculations in more detail elsewhere, along with descriptions of the prevalent groundwater and drainage systems operative in the IID (Rhoades, 2003b). The equation number given herein are renumbered compared to those used in the latter more comprehensive Report, whereas the table and figure reference numbers are the same as used in these reports (the particular reference is identified for each table and figure). The references are also found in the comprehensive reports. A preliminary, less rigorous report on my evaluation of the mass balance method to estimate tailwater and deep percolation volumes in the IID was provided to the USBR (Rhoades, 2003); my comprehensive Report to the Metropolitan Water District of Southern California (Rhoades, 2003b) supplants the earlier preliminary one. Chloride was used herein, rather than Selenium or TDS, because it is less affected by chemical reactions and, hence, is the most suitable solute for which there is available adequate data.

A. Setmire Approach

Setmire, et al. (1993, 1996) suggested that the proportions of surface and sub-surface flows making up the Alamo River flow at its point of discharge to the Salton Sea (or of the waters found in the surface drainage ditches) that are derived from the imported Colorado River water could be determined by comparing concentrations of selenium and other constituents in the Alamo River with the analogous concentrations in the surface drainage waters and with the analogous concentrations in the tilewater flows. The mass balance proposed by Setmire is possible because, supposedly, 99 percent of the Alamo River flow (and it should be equally as high in the surface drains) is composed of delivery losses and drainage-related waters, tilewater flows reflect the concentration of sub-surface drainage flows and because spill and tailwater act to dilute the sub-surface flows. Setmire, et al. (1993, 1996) assumed that the operational spill water, seepage and tailwater would have the same concentration as the delivered Colorado River water and that the components making up the sub-surface inflows to the surface drainage canals and Rivers all had the concentration of the tilewater. Assuming the volume of the Alamo River (or of open drain ditch water) is composed solely of just these flows, the proportions of surface drainage (x) and sub-surface (1-x) drainage waters comprising the volume of the Alamo River (or of open drain ditch water) is determined from the following relation containing the three constituent-concentrations:

(Alamo River conc.) = (x)(surface water conc.) + (1-x)(sub-surface water conc.). [2]

Equation 2 is simply a two-component mixing model; it is the same relation one would use to calculate the weighted averaged concentration of the mixture formed of two components each having a unique concentration of the same conservative constituent. An equivalent relation is,

$$x = (C_{sub} - C_M)/(C_{sub} - C_{surf}), \qquad [3]$$

where C_{sub}, C_{surf} and C_M are the concentrations of the sub-surface drain water ("tilewater"; assumed to be comprised of deep percolation plus seepage water), the surface drainage water (assumed to be comprised of tailwater and spill) and the Alamo River (or surface canal waters comprised of the mixture of the sub-surface and surface drainage waters), respectively; x is the proportion of the total volume of the mixture (combined effluent; drainage-related water) that is derived from the surface water component having concentration C_{surf} and (1-x) is the proportion derived from the sub-surface water component having concentration C_{sub}.

For illustrative purposes, the application of the above two-category mixing/dilution model to estimate tailwater and deep percolation volumes is applied in this paragraph and in the next using the same concentrations used by Setmire et al. (1996). However, the values of Setmire are refined and used for final analysis purposes in a following paragraph. Setmire et al., (1996) used a mean chloride concentration of 92 mg/l to represent the concentration of the surface water (essentially imported Colorado River water as received for use in irrigation, which is the mean concentration of 11 water samples collected from the East Highline Canal during the period October 1988 through August 1989; see Table 5 in Schroeder, et al., 1993), a median chloride concentration of 1200 mg/l for the tilewater (the median chloride concentration of the 303 tilewater samples collected in August 1994 through January 1995; these data are given in Appendix A of Setmire, et al., 1996) to represent the concentration of the net deep percolation that resulted from the evapotranspiration and leaching of the applied irrigation water (the surface water; Colorado River water), and a median chloride concentration of 420 mg/l for the combined mixture of surface and sub-surface drainage flows (the median chloride concentration of the 48 open drainage canal water samples collected in August 1994; these data are given in Appendix C of Setmire, et al., 1996; the median chloride concentration of eleven samples of the Alamo River collected near its outlet to the Salton Sea in August 1994-January 1995 was 520 mg/L (see Table A3 in Rhoades, 2003b). The resulting values of x and of 1-x using the values of Setmire are about 0.704 and 0.296, respectively. Because the irrigation-related effluent volume of the IID service area is one-third of the water delivered to IID, the fraction of the delivered water that is sub-surface water is about 0.10 (= 0.296 * 0.33), assuming the results of Equation 2 can be extended to the entirety of the IID service area.

The proportions determined by Setmire can be transformed into volumes by assuming that the sum of the irrigation/drainage-related flows from the IID service area plus the volumes of unconsumed rainwater and M&I discharging to the "open-drains" total 1,079,000 AF (obtained from the water balance data given in Figure 3.1-16 of the IID 2002 EIR/EIS Report). Thus, the volume of the surface–drainage component (tailwater plus spill water) of the combined drainage-related flow mixture would be estimated by the Setmire "results" given above to be about 759,600 AF (0.704 times 1,079,000 AF) and, correspondingly the subsurface component (deep percolation plus seepage) would be estimated to be about 319,400 AF (0.296 times 1,079,000 AF). In turn, the volume of tailwater would be estimated to be about 614,000 AF; this is obtained by deducting the sum of the volumes of spill, M&I discharge-flows and one-half rainfall not consumed in ET (totaling 145,500 AF, as given in Figure 3.1-16 of IID, 2002) from the total surface drainage component volume of 759,600 AF. Analogously, the estimated volume of deep percolation would be 188,900 AF (obtained by deducting the volume of seepage and one-half of the unconsumed rainfall, totaling 130,500 AF, as given in Figure 3.1-16 of IID, 2002, from the total sub-surface drainage component volume of 319,400 AF). These results are given elsewhere (in Table 1 of my comprehensive Report; Rhoades 2003b), along with others estimated analogously for other assumed combinations of chloride concentrations.

Sensitivity Analyses. Obviously, one can get somewhat different estimates of tailwater and deep percolation volumes using different values for the three input concentrations. For example, as a sensitivity analysis, if CL_{surf} is varied from 69 to 145 mg/l (bracketing the 92 mg/l of Setmire and including near historical ranges of Colorado River water), while holding CL_M and CL_{sub} constant at values of 420 and 1200 mg/l, respectively, the volumes of tailwater and deep percolation fall within the limits of about 599-652 KAF and 151-204 KAF, respectively. If CL_M is increased from 420 to 550 mg/L while holding CL_{surf} and CL_{sub} constant at values of 92 and 1200 mg/l, respectively, the volumes of tailwater and deep percolation decrease and increase, respectively, by about 127 KAF. If CL_{sub} is increased from 1200 mg/l to 1400 mg/l, while holding CL_{surf} and CL_M constant at values of 92 and 420 mg/l, respectively, the volumes of tailwater and deep percolation increase and decrease, respectively, by about 49 KAF with respect to the median values. While such variations in concentrations change the results, it is interesting to note that none result in tailwater and deep percolation proportions like those reported by IID (IID, 2002), where IID suggested an average tailwater volume of 386,000 AF per year and an average deep percolation volume of 417,000 AF per year. Results from the Setmire approach and sensitivity analysis do, however, compare quite well to the independently calculated "WATSUIT" estimate of 617,000 AF of tailwater.

Improved Estimates. After a preliminary analysis (Rhoades, 2003), I examined the available data to determine the most appropriate concentration data to use in my analysis of tailwater and deep percolation volumes I examined the available data. Three sets of sub-surface drainage water data have been located that potentially can be used for this assessment and four sets of surface water data were located that potentially can be used.

These data are described in my comprehensive Report, along with my reasons for selecting the data I chose to use in my comprehensive assessment reported briefly herein. For the purpose of my improved assessment, I used the chloride concentration of the 48 samples collected from the surface drainage channels throughout the IID service area by USGS (the 1994 data set reported by Setmire, et al., 1996) to represent the mix of irrigation/drainage-related waters in the IID during this period; the median chloride concentration of this sample-set is 420 mg/l, the mean concentration is 503 mg/L and the flow-weighted chloride concentration is 455 mg/l. The flow-weighted value of 454 mg/L is considered to be a more valid representation of drain concentrations than is the value of 420 mg/L used by Setmire. I have also compared the results obtained from these samples with those obtained using concentration data for the Alamo River at drop 3 (537 mg/l). The Alamo River at drop 3 represents an integration of various drainage channels, but may possibly be slightly impacted by upward flow of quite saline artesian ground water.

For the analyses in this paper, I used the instantaneous-discharge weighted chloride concentration determined in the most extensive data set available (the 303 sample-set reported by Setmire et al., 1996) as representative of the tile drainage water. The values were weighted for time, discharge rate and spatial distribution within the IID service area.

For the chloride concentration of surface water, I used two different chloride concentrations for the two different mass balance approaches used in this study. For the improved Setmire approach, I used the 1994 mean Colorado River water chloride concentration of 125 mg/l; for the Rhoades approaches, described later, I used the 1991 mean Colorado River water chloride concentration of 117 mg/l, since it represents the water that was applied about 4-5 years prior to the time of the collection of the sub-surface drainage waters. The estimate of the time lag between when water is applied and when it is all discharged in the tile drains is approximately 5 years, as discussed in my Comprehensive Report. Thus, the concentration data that I used to estimate the volumes of tailwater and deep percolation in IID are for the most current time period (1994) for which all the required data exist and the sample numbers are deemed sufficient in this regard. These concentrations are given in Table 3 (Rhoades, 2003b), along with their standard deviations. I did not make assessments for earlier years or later years, because the required data are not available for the same time periods and the sample numbers are not sufficient. In the Setmire application, I modified the 125 mg/l of Colorado River water for 1984 to account for higher salinity of tailwater as compared to spilled canal water. This was done by iteratively calculating the volume of tailwater and weighting the C_{surf} value according to volumes of tailwater, spillage, M&I effluent and rain (assumed to have 0 chloride). The tailwater concentration was estimated as 1.19, which is the weighted average of 1.30 for 62 percent of the area having cracking soils and of 1.0 for the other 38 percent of the area; based on information contained in NRCE, 2002. The final estimate for C_{surf} was 141 mg/l, which is 1.13 times 125 mg/l.

Based on values for C_M, C_{sub} and C_{surf} of 455, 1545, and 141 mg/l, the values for tailwater and deep percolation were 693,000 and 110,000 AF/year (see Table 4b; Rhoades, 2003b). Values for x and 1-x were 0.777 and 0.223. Based on values for C_M, C_{sub} and C_{surf} of 537, 1545, and 141 mg/l, the values for tailwater and deep percolation were 629,000 and 174,000 AF/year. Values for x and 1-x were 0.718 and 0.282. The first values use flow-weighted average concentrations in open drainage channels, whereas the latter values use concentrations of the Alamo River at drop 3. These values for tailwater and deep percolation represent improved estimates over the values of Setmire et al. (1996). However, the two improved estimates for tailwater are only 79,000 and 15,000 AF (11 and 2%) different from the tailwater estimate based on original concentration values of Setmire. The improved estimate of tailwater is 76,000 acre-feet more (about 12 percent) than the independently calculated "WATSUIT" estimate of 617,000 acre-feet, whereas, the improved estimates for tailwater and deep percolation are 307,000 and 243,000 AF different (44 and 39%) from the amounts estimated by IID (2002).

B. Other Approaches

Because the volume and chloride concentration of the Alamo River (or of the analogous surface drainage waters) are comprised of and affected by both system (seepage and spill) and on-farm derived sources of irrigation/drainage-related flows (tailwater and deep percolation), as well as potential additions by outside sources having potentially high chloride concentrations, for example, groundwater and, possibly Salton Sea intrusion, it may be preferable, in some cases, to estimate the on-farm volumes of interest (tailwater and deep percolation) using relationships that are more directly related to on-farm processes. With this in mind, I developed several alternative mass balance approaches and relationships for a number of distinctively different systems of sub-surface flow. I will now describe these approaches and results.

Rhoades Approach: Method 1

The simplest model of the sub-surface drainage system that may apply to the prevailing IID service area is described by the following set of conditions: the chloride concentration in the infiltrated irrigation water is the same as that in the applied water (no significant amount of horizontal leaching occurs), and the same amount of chloride salt contained in the infiltrated water is subsequently discharged in the deep percolation from the rootzone. In other words, a quasi steady-state exists on about an annual basis; a panel of experts has also concluded that the IID service area is essentially at steady-state after these many years of irrigation and leaching, Amrhein (2001). An additional condition is that the water collected by the tile drainage system has the same concentration as that of the deep percolation water (i.e., there is no other sub-surface source of chloride that contributes to the tile water effluent concentration).

With the above assumptions, the volume fraction of infiltrated water that is discharged as deep percolation (the leaching fraction, V_{dp}/V_{infw}) can be determined, as well as the volume of water that was infiltrated (V_{infw}), as follows, with reference to the water and salt balance of the on-farm crop rootzone (the derivations of these relations are given in my comprehensive mass balance report):

$$LF_{infw} = (V_{dp}/V_{infw}) = C_{iw}/C_{tile}, \qquad [4]$$

$$V_{infw} = (V_{et} - V_{rw})/(1 - LF_{infw}). \qquad [5]$$

The corresponding volume of tailwater can be estimated, in turn, from knowledge of the total volume of water delivered on farm, since:

$$V_{tw} = V_{iw} - V_{infw}, \quad [6]$$

or,

$$V_{tw} = V_{iw} + V_{rw} - V_{et} - V_{dw}. \quad [7]$$

Effective rainwater is omitted from Equation [7] because this volume of water is, by definition, fully consumed in evapotranspiration or leaching.

As with the Setmire approach, one will get somewhat different estimates of tailwater and deep percolation volumes using different values for the chloride input concentrations. However, the effect of an increase in CL_{infw} (i.e., salinity of the Colorado River) on the estimate of tailwater and deep percolation volumes with the Rhoades Approach is opposite to the effect of an increase in CL_{surf} concentration in the Setmire Approach. The volume of tailwater increases, but not greatly, as CL_{tile} increases. Data to illustrate this are given in my comprehensive mass balance report.

The estimates of tailwater and deep percolation that I obtained with the Rhoades Approach I method using the most representative estimates of chloride concentrations for the applied water and tilewater (given the available data; see Table 3; Rhoades, 2003b) for the 1994 period (117 mg/l and 1545 mg/l, respectively) are about 663,000 and 140,000 acre-feet, respectively.

The estimates of tailwater and deep percolation volumes obtained by the Rhoades Approach 1 method are similar to those obtained by the Setmire Approach (they actually fall between the estimates from the "Setmire" approach for the two values for C_M). The tailwater estimate by Rhoades I is within 3 percent of that derived by the "WATSUIT" calculation. In addition, the tailwater volume estimates vary in an opposite direction as those by the Setmire approach as the chloride concentration of the infiltrated water (surface water) is varied. As explained in my comprehensive mass balance report, the Setmire Approach is prone to underestimate tailwater volumes, if the surface drainage water (the mixed water assumed in this method to be solely comprised of surface water plus sub-surface water having a chloride concentration identical to that of the tilewater) receives any direct inputs of brackish groundwater. On the other hand, the Rhoades Approach is prone to underestimate deep percolation if the tilewater is "contaminated" by the inflow of substantially saline groundwater.

Rhoades Approach: Method 2

A refined "view" of the operative sub-surface drainage and shallow groundwater hydrogeology for the IID service area is that the tile drainage system underlying an individual field does not necessarily "capture" all of the deep percolation from that particular field, and that the un-intercepted deep percolation flows into the shallow groundwater (water table) and mixes with it. In this model, this shallow groundwater is comprised solely of deep percolation and canal seepage and it is isolated from deeper groundwater systems by an underlying relatively impervious layer of dense clay. The tile drain lines are far enough away from the irrigation canals so that the tilewater concentration is little affected by seepage. The shallow groundwater generated by deep percolation events flows at very slow rates towards the axis of the Valley and towards the Salton Sea. Most of this flow is picked up by the tile drainage systems underlying other parts of the same field or other fields along the flow path and, hence, is eventually mostly discharged as tilewater drainage into the open drains, although some of it flows directly into these deeper open surface-drains and some flows directly into the Alamo and New Rivers. Additionally, some of the shallow groundwater is consumed in evapotranspiration by deep-rooted crops growing in the "down-gradient" fields. The assumption is made that no additional salt from any other source is added to the tilewater or to the shallow groundwater during this flow-journey; the salt and water contained in the shallow groundwater and in the tilewater are derived solely from deep percolation and seepage of imported Colorado River water.

In this model, the chloride concentration of the tilewater reflects the consumptive-use of some of the excessive deep percolation that occurs in the higher-lying more coarse-textured fields by deep-rooted crops grown in lower-lying fields, through capillary rise of some of this water into the rootzones of these crops. The seepage water effectively becomes part of the net deep percolation, since some of it is consumed in crop evapotranspiration by deep-rooted crops. Thus, the average chloride concentration of the tilewater is indicative of the net leaching fraction across the entire IID service area, including the use of some excessive deep percolation generated in the outer areas of coarser textured soils in the IID service area in evapotranspiration by "deep-rooted" crops being grown in the lower lying "trough areas" of the area. This redistribution of deep percolation and seepage and the consumption of water from the shallow groundwater (water table) helps explain why the overall LF_{infw} value that is determined by this method is as low as it is and why the overall target District on-farm irrigation efficiency can be high (say 0.95 when there is no tailwater), when as much as 38 percent of the soils of the IID service area are non-cracking and more permeable types, which are prone to excessive deep percolation and lower field irrigation efficiencies compared to the high clay-content cracking soils.

In this approach, salt removal from the cracking soils by horizontal-leaching and tailwater runoff is included. The factor (F_{ctw}), which is used to represent the relative increase in salinity (chloride, in this calculation) compared to the applied water, is assumed to be 1.19 (which is the weighted average of 1.30 for 62 percent of the area having cracking soils and of 1.0 for the other 38 percent of the area; based on information contained in NRCE, 2002). The appropriate equations for this approach follow (their derivations are given in my comprehensive mass balance report):

$$V_{dp}/V_{iw} = (1 - F_{tw}\,F_{ctw})(C_{iw}/C_{tile}), \qquad [8]$$

where F_{tw} and F_{ctw} are the tailwater fraction (V_{tw}/V_{iw}) and the tailwater concentration factor (C_{tw}/C_{iw}), respectively. The value of F_{tw} needed to solve

Equation [8] and the volume of tailwater can be determined from Equations [9] and [109], respectively:

$$F_{tw} = [\Delta - (C_{iw}/C_{tile})]/[1-(F_{ctw})(C_{iw}/C_{tile})], \qquad [9]$$

where, Δ is the ratio $[(V_{iw} + V_{rw} - V_{et})/(V_{iw})]$, and, by definition

$$V_{tw} = F_{tw}(V_{iw}). \qquad [10]$$

The estimates of tailwater and deep percolation obtained with the Rhoades Approach II method using the estimates of chloride concentrations in the applied water and in the tilewater that are considered to be the most representative (given the available data) of the IID situation for the 1994 period (117 mg/l and 1544.6 mg/l, respectively) are about 674,000 and 130,000 acre-feet, respectively. These results are similar to those obtained by the Rhoades Approach 1 method, although the tailwater volume is a little higher and the deep percolation volumes are a little lower. The results obtained by a statistical appraisal will be described next.

Analysis of Uncertainty in the Estimated Volumes of Tailwater and Deep Percolation

The Setmire and Rhoades Approaches (for estimating tailwater and deep percolation volumes) depend on both hydrological and chemical data. There is uncertainty in all of these input data and, hence, in the estimations of tailwater and deep percolation (the outputs) obtained using them. One way to determine the uncertainty in the output estimates is through statistical simulation analysis. In such an analysis, simulated probability distributions are imposed on the various input values. These N sets of simulated inputs are then used to calculate N corresponding sets of output estimates (tailwater and deep percolation volumes). Means, standard deviations and confidence intervals can then be established for the estimates of tailwater and deep percolation. Such statistical analyses were performed on these data to evaluate the uncertainty and expected ranging in the estimates of the volumes of tailwater and deep percolation made herein with the Setmire and Rhoades Approaches and associated data sets.

Because the Setmire and Rhoades Approaches are each subject to potential errors from the input of water and salt from "geologic" origin, but are impacted in opposite "directions", the use of the average values of the two tailwater volumes and of the two deep percolation volumes obtained by the separate Approaches, are likely to be more accurate, as is shown in my comprehensive approach.

For the statistical analysis, the means and standard deviations of the input parameters used are those listed in Table 3 (Rhoades, 2003b). The standard deviations of the volumes were obtained from the WST Report (1998). The standard deviations of the chloride concentrations were calculated from the raw data obtained from the Setmire, et al. (1996) Report, the USGS Monthly Stream Flow Statistics and USBR Yuma Analytical Laboratory database and associated flow rates or volumes, using flow-weighting methods.

The simulation analysis was performed using SAS (version 8.0). The simulation sample size used in the analysis was N = 10,000 for each approach and for the average of the two approaches.

The estimated volumes of tailwater and deep percolation obtained from the simulation analysis using the average values from the above-described separate estimates are given in Table 4b (Rhoades, 2003b), along with their confidence intervals. Additionally, 90% two-sided confidence intervals and 90% and 95% upper or lower confidence end-points are given for the mean volumes. Histogram plots of the predicted probability distributions are given in my comprehensive mass balance report, as are more details of the statistical analysis. The estimated volumes of tailwater (the one based on the use of Alamo River water and the use of the drainage canal water in the "Setmire calculations") ranged from 637 to 670 KAF and deep percolation ranged between about 130 and 165 KAF, respectively. Only the Rhoades Approach 1 estimates were used in these averages, since the inclusion of horizontal leaching has a minimal effect, as shown earlier. These ranges and the bounds of these volume estimates are reduced compared to those separately determined. The standard deviations are not substantially different, because the uncertainties associated with the water volumes and the chloride concentrations used in the calculations are the same. The estimated lower bounds for tailwater volume ranged from 523 to 563 KAF, depending upon which value of chloride concentration was used (455 or 537 mg/l). On the other hand, the estimated upper bounds for the volume of deep percolation ranged from 190 to 229 KAF, depending upon which value of chloride concentration is used. Thus, this analysis suggests that the tailwater purported by IID (2002) (386 KAF) is well below the statistically expected minimum possible value for tailwater (533 KAF).

Discussion of Results and Comparison of Approaches

The results obtained from the statistical analysis for the separate and combined Approaches are given in Table 5b (Rhoades, 2003b), to facilitate comparison. These data show that the volumes of tailwater and deep percolation obtained by all of these various approaches are similar to each other when compared at equivalent concentrations of chloride. For example, the estimates of tailwater and deep percolation obtained with the Setmire Approach, assuming the chloride concentration of the mixed water receiving the drainage flows is 536.8 mg/l, are about 618 KAF and about 186 KAF, respectively. The analogous estimates obtained with the Rhoades Approach 2 method are about 668 KAF and 134 KAF, respectively. The two estimated volumes of tailwater fall within the range of 618 KAF to 668 KAF, while the two deep percolation volumes fall within the range of 134 KAF to 186 KAF.

Neither Approach may be demonstrated to be superior to the other, given the available information. Both should be satisfactory assuming the absence of factors that could cause errors. The Setmire Approach will underestimate the tailwater volume and overestimate the volume of deep percolation if saline groundwater is part of the body of mixed water (Alamo River or surface drainage canals) used to represent the drainage-flow water of the IID service area. On the other hand, the Rhoades Approach will underestimate the volume of deep percolation and overestimate the tailwater volume, if saline groundwater (more saline than the deep percolation) is collected by the tile drainage system. Since these errors are opposite in effect, the best estimate of the volumes of tailwater and deep percolation are likely those obtained by averaging the two sets of corresponding volumes. Accordingly, my best estimate of tailwater volume for the IID service based on chloride balance considerations is 637,400 acre-feet and the best estimate of the volume of deep percolation is 165,400 acre-feet. I used the Setmire Approach values based on the concentration of 537 mg/l in this averaging, because they represent the lowest and highest estimates of tailwater and deep percolation, respectively (hence, are the most favorable to IID (i.e., closest to IID, 2002)). Example calculations show that such an averaging procedure results in estimates of both tailwater and deep percolation volumes that are apt to be more exact and true than are the corresponding estimates obtained from either Approach alone, if both Approaches are considered to be subject to "contamination" by saline groundwater inflows into the surface drainage waters (Alamo River or open drain canals), in the case of the Setmire Approach, and into the tile drainage system, in the case of the Rhoades Approach (see my comprehensive mass balance report).

The apparent leaching fraction corresponding to the estimate of deep percolation with the Setmire Approach is about 0.10 (= 185.6/(2508-617.7); that estimated with the Rhoades Approach is about 0.08 (= 117/1544.6). Based on the combined results described in the preceding paragraph, the best estimate of the leaching fraction of the IID service area is about 0.09 ((= 165.4/(2508-637.4)). The apparent percentages of tailwater corresponding to the estimate of tailwater volume with the Setmire Approach is about 25 percent of farm deliveries (= 617.7/2508); that estimated with the Rhoades Approach is about 26 percent of farm deliveries (= 657.1/2508). Based on the combined results described in the preceding paragraph, the best estimate of the tailwater percentage of the IID service area is about 25 percent of farm deliveries (= 637.4/2508).

Based on the above described best estimate for the total deep percolation volume of 165,400 AF in the IID and for the required leaching volume (RV_{dw}) of approximately 103,000 AF for 2003 (see Table 13a; Rhoades, 2003a), the additional deep percolation from IID farms is estimated to be about 62,400 AF per year, provided the chloride results are applicable to 2003 (and there is no reason to believe that the IID-wide volume of deep percolation will be substantially different at present, given the following conclusion about limited permeability). This additional deep percolation difference corresponds to a IID-wide value for F_n of about 0.97 ((determined from the following equation given in Table 4a, $F_n = \{[(RV_{et} + RV_{dw})]/[(RV_{et} + RV_{dw}$ + excess volume of deep percolation)]})), which is close to but slightly higher than the value of 0.95 that was used herein to calculate the irrigation water requirement. This result suggests that a value of about 0.97 may represent a physical limit for this parameter, associated with the very low vertical percolation rates of the clay soils in IID. It also supports the reasonableness of the value of 0.95 that was determined independently of this "chloride-balance derived data" and used herein to calculate the on-farm water requirement.

Comparison of Mass Balance Estimates With IID Estimates

As discussed earlier, each of these the two chloride mass balance approaches utilized herein is based on different assumptions and on somewhat different required data. Each has advantages and disadvantages. Yet both approaches yielded estimates of the volumes and proportions of tailwater and deep percolation that are similar to one another, but which are very different from those suggested by IID (as given in Figure 3.1-16 of IID, 2002). The IID (2002) data are summarized as follows, in acre-feet per year for the 1987 to 1998 period:

On-farm delivery = 2,508,000
Effective rainfall = 101,000
Delivered + effective rain = 2,609,000
Infiltrated water = 2,233,000 (= delivery + rainfall – tailwater)
Tilewater = 417,000 (18.7% of infiltrated; 16.0% of delivery + rain)
Tailwater = 386,000 (15.4% of delivered; 14.8% of delivered + rain)
Implied total drainage water = 803,000 (delivery + effective rainfall – ET)
ET = 1,860,000

Note that the LF_{infw} value (0.19 = 417,000/2,233,000) corresponding to the IID data is higher than what seems reasonable, considering the prevalent soils, crops and weather and the leaching fraction estimated by the chloride data (about 0.08-0.10). While the volume fraction of tailwater estimated by IID is about that required by their regulations (equivalent to about 15 percent of the delivered water), it is much lower than that estimated by the chloride mass balance assessments described herein, which were about 25 percent, and that (about 23 percent) estimated from about 1200 measurements made in 1982 and 1983 and representing about 14,000 acres of irrigated land throughout the IID service area, as reported by USBR (1984) in their cooperative study with the IID.

The average chloride balance determined tailwater volume (637,000 AF) is 251,000 AF greater than the tailwater volume purported by IID (386,000 AF).

Most References cited herein are given in following two comprehensive reports

Rhoades, J D. 2003a. Assessment of the leaching and on-farm irrigation water requirements of Imperial Irrigation District. A Special Report for the Metropolitan Water District of Southern California, May 17, 2003.

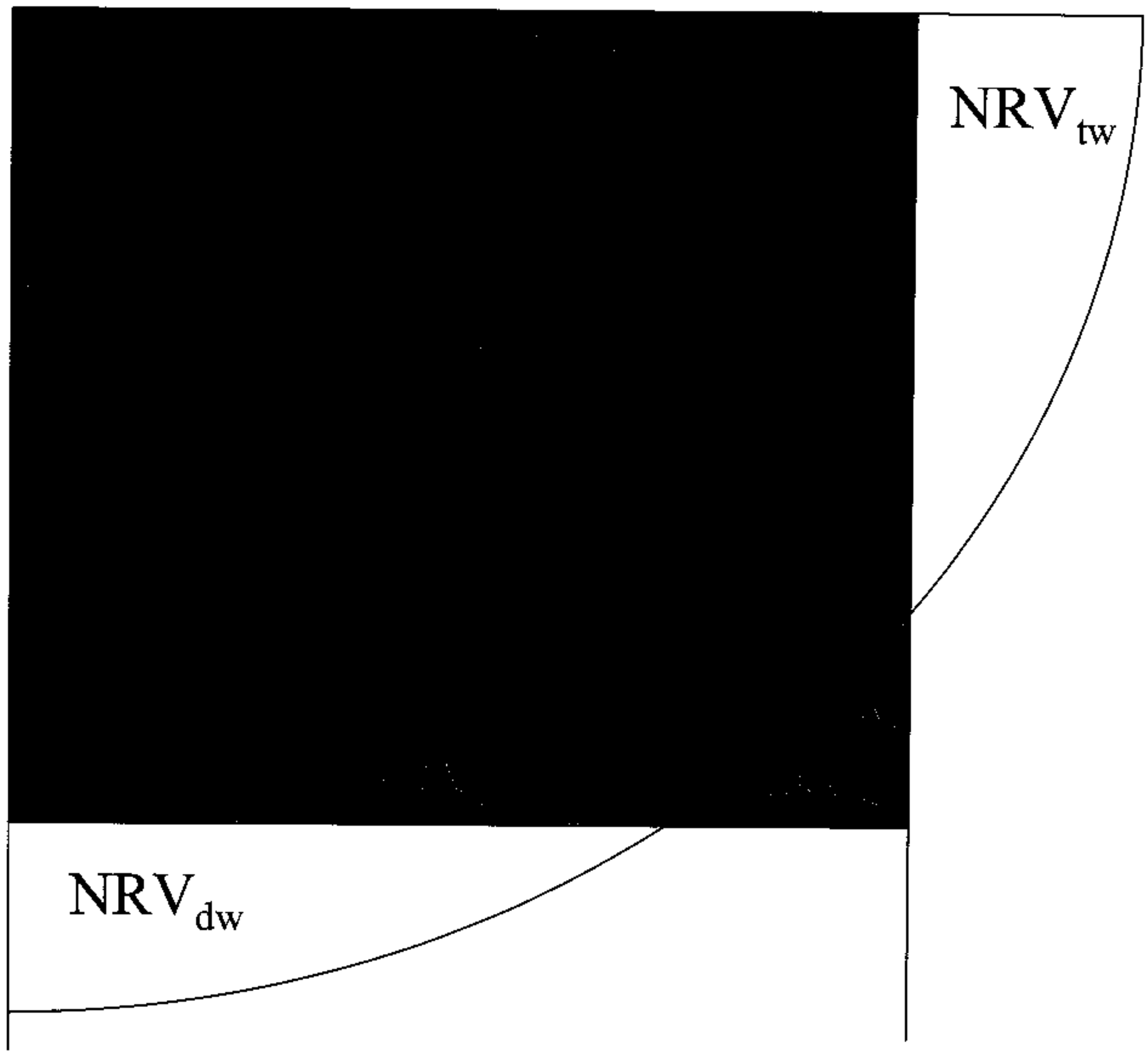
Rhoades, J.D. 2003b. Estimation of volumes of tailwater and deep percolation in the IID service area using chloride mass balance relationships. A Special Report for the Metropolitan Water District of Southern California, May 19, 2003.

Other references cited but which are not given in the above two reports

Jensen, M. E. and I. A. Walter. Assessment of 1997-2001 Water Use by the Imperial Irrigation District. Special Report prepared for the US Bureau of Reclamation, November, 2002.

Scott, J. 2003b. Imperial Irrigation District, diversions, return flows, losses, deliveries, and other related hydrologic data. Memorandum to Mr. A. K. Dimmitt, The Metropolitan Water District of Southern California, May 20, 2003.

Figure 2. Schematic of Potential Destinations of Applied Irrigation Water



$$RV_{et} = BRV_{et} + URV_{et};\ RV_{dw} = BRV_{dw} + URV_{dw}$$

Table 1c Crop Consumptive Use of Colorado River[1], in acre-feet per year				
	time period			
crop	2000	2001	2002	average
alfalfa	810530	823294	843827	825884
sudan	159071	149877	141792	150247
wheat	83307	69626	78146	77026
bermuda	231510	262803	280736	258350
sugar beets	101656	84401	80952	89003
lettuce-early	14141	13995	15203	14446
lettuce-late	6645	6577	7144	6789
carrots	32696	29457	31051	31068
cantaloupes-spring	15663	13392	13083	14046
cantaloupes-fall	838	1032	1762	1211
alfalfa seed	22706	10043	11051	14600
cotton	19282	44560	30515	31452
honeydew	2666	3281	2300	2749
watermelon	3652	1535	2087	2425
onions	32517	23488	21607	25871
onion seed	12998	6648	6253	8633
rye-pasture	6241	5008	2009	4419
oats & barley	1277	3898	9963	5046
misc field crops	17913	24445	24568	22309
tomatoes	2102	2099	1731	1977
potatoes	4120	3530	2133	3261
brocolli	8961	6721	5976	7219
cabbage	1063	950	868	960
cauliflower	3358	3041	2675	3025
corn-ear	14692	9515	12370	12192
misc garden crops	2634	2745	2357	2579
asparagus	23257	17273	14465	18332
citrus	27302	27161	27671	27378
jojoba	7	7	0	5
peach trees	32	33	33	33
permanent pasture	2434	2633	2781	2616
~~sub-totals:~~	~~1665271~~	~~1653068~~	~~1677109~~	~~1665149~~
~~Duck ponds~~	~~23363~~	~~23814~~	~~25005~~	~~24061~~
fish farms	4685	4283	4382	4450
~~totals:~~	~~1693319~~	~~1681165~~	~~1706496~~	~~1693660~~
~~updated totals:~~	~~1732940~~	~~1720980~~	~~1747480~~	~~1733800~~
[1] ~~excludes effective rainfall~~				

Table 2. Average Compositions of the Colorado River (at Imperial Dam), During the Period 1987-2002 [1]										
		TDS-180,	concentrations in meq/L							
period	EC, dS/m	mg/L	Na	K	Ca	Mg	ALK	Cl	SO_4
1987	1.001	651.6	4.15	0.12	3.74	2.36	2.88	2.33	5.10
1988	1.038	674.6	4.52	0.10	3.57	2.35	2.85	2.53	5.48
1989	1.084	693.7	4.72	0.10	3.90	2.32	2.81	2.64	5.71
1990	1.151	754.6	5.17	0.11	4.08	2.41	2.94	2.99	6.00
1991	1.217	802.7	5.47	0.12	4.35	2.77	3.01	3.30	6.17
1992	1.224	824.8	5.66	0.13	4.39	2.83	3.03	3.38	6.40
1993	1.239	824.6	6.01	0.13	4.29	2.75	2.93	3.51	6.29
1994	1.251	844.7	5.85	0.13	4.47	2.80	2.93	3.52	6.42
1995	1.267	834.2	5.94	0.13	4.32	2.74	2.98	3.59	6.44
1996	1.245	830.4	5.57	0.13	4.21	2.64	2.95	3.60	6.27
1997	1.148	752.6	5.20	0.12	4.05	2.41	2.87	2.99	5.73
1998	1.053	676.3	4.37	0.10	3.87	2.43	2.82	2.51	5.48
1999	1.080	685.7	4.72	0.11	3.97	2.31	2.94	2.63	5.75
2000	1.059	684.3	4.58	0.11	3.93	2.29	2.95	2.61	5.22
2001	1.102	713.7	4.97	0.10	3.98	2.41	2.83	2.84	5.54
2002	1.110	695.7	4.77	0.11	3.97	2.42	2.98	2.86	5.54
1989-1996	1.213	803.9	5.77	0.12	4.26	2.66	2.95	3.33	6.23
1987-2001	1.143	749.5	5.22	0.12	4.07	2.52	2.97	3.00	5.86
2000-2002	1.091	698.1	4.77	0.11	3.96	2.38	2.92	2.77	5.44

[1] USBR Yuma Desalting Plant Laboratory; average of approximately 24 samples per year

Table 3[j]. Salt-Tolerances, Volumes (in AF) of Crop ET, of Required Deep Percolation (RV_{dw}) and of Required Infiltration Water (RV_{infw}) and Individual and IID-wide Leaching Requirements (LR_{infw}), for Year 2000-2002; EC_{iw} of 1.0909 dS/m

crop	EC_e [a]	LR_T [b]	LR_W [b]	average CU	$RV_{dw,T}$ [c]	$RV_{dw,W}$ [c]	$RV_{infw,T}$ [d]	$RV_{infw,W}$ [d]
alfalfa	2.0	0.122	0.060	825884	115238	53025	941122	878909
sudan	2.8	0.085	0.028	150247	13869	4348	164116	154595
wheat	6.0	0.038	0.005	77026	3021	386	80047	77412
bermuda	6.9	0.033	0.004	258350	8721	943	267071	259293
sugar beets	7.0	0.032	0.004	89003	2959	314	91962	89317
lettuce-early	1.3	0.202	0.160	14446	3649	2758	18095	17204
lettuce-late	1.3	0.202	0.160	6789	1715	1296	8504	8085
carrots	1.0	0.279	0.291	31068	12026	12732	43094	43800
cantaloupes-spring	1.0	0.279	0.291	14046	5437	5756	19483	19802
cantaloupes-fall	1.0	0.279	0.291	1211	469	496	1680	1707
alfalfa seed	2.0	0.122	0.060	14600	2037	937	16637	15537
cotton	7.7	0.029	0.003	31452	945	89	32397	31541
honeydew	1.0	0.279	0.291	2749	1064	1127	3813	3876
watermelon	1.0	0.279	0.291	2425	939	994	3364	3419
onions	1.2	0.222	0.192	25871	7392	6156	33263	32027
onion seed	1.0	0.279	0.291	8633	3342	3538	11975	12171
rye-pasture	7.6	0.030	0.003	4419	135	13	4554	4432
oats & barley	8.0	0.028	0.003	5046	146	13	5192	5059
misc field crops	4.0	0.058	0.013	22309	1366	283	23675	22592
tomatoes	2.5	0.096	0.036	1977	209	75	2186	2052
potatoes	1.7	0.147	0.087	3261	563	312	3824	3573
brocolli	2.8	0.085	0.028	7219	666	209	7885	7428
cabbage	1.8	0.138	0.077	960	154	80	1114	1040
cauliflower	2.8	0.085	0.028	3025	279	88	3304	3113
corn-ear	1.7	0.147	0.087	12192	2105	1165	14297	13357
misc garden crops	1.8	0.138	0.077	2579	413	214	2992	2793
asparagus	4.1	0.056	0.012	18332	1092	220	19424	18552
citrus	1.3	0.202	0.160	27378	6916	5227	34294	32605
jojoba	4.0	0.058	0.013	5	0	0	5	5
peach trees	1.7	0.147	0.087	33	6	3	39	36
permanent pasture	5.6	0.041	0.006	2616	111	15	2727	2631
totals:				1665151	196981	102812	1862132	1767963

IID-wide $LR_{infw,T}$ = total $RV_{dw,T}$ / total $RV_{infw,T}$ = (196981)/(1862132) = 0.105783

IID-wide $LR_{infw,W}$ = total $RV_{dw,T}$ / total $RV_{infw,W}$ = (102812)/(1767963) = 0.058153

[a] obtained from Maas and Grattan (1999) in dS/m

[b] $LR_{infw,T}$ and $LR_{infw,W}$ are the individual crop LR_{infw} values for the Traditional (T) and WATSUIT (W) models, respectively .

[c] $RV_{dw,T}$ and $RV_{dw,W}$ are the required drainage volumes corresponding to $LR_{infw,T}$ and $LR_{infw,W}$ values, respectively.

[d] $RV_{infw,T}$ and $RV_{infw,W}$ are the required drainage volumes corresponding to $LR_{infw,T}$ and $LR_{infw,W}$ values, respectively

Table 4a. Summary of Some of the LR-Related Relationships of J. D. Rhoades

Symbol[a]	Mathematical Relationships[b]
	use when including LR in calculations
LR	$LR = LR_T$, or LR_W
LR_{infw}	$LR_{infw} = [(1 - F_{tw}{}^{c}F_{ctw}{}^{d})/(1 - F_{tw})](LR)$; or $LR_{infw} = LR_{iw}/(1-F_{tw})$, if $F_n = 1$
LR_{iw}	$LR_{iw} = (1-F_{tw}F_{ctw})(F_n)(LR)$; or $LR_{iw} = (1-F_{tw})(F_n)(LR_{infw})$, if $F_n < 1$
TLR_{iw}	$TLR_{iw} = LR_{iw} + (BV_{tw} / RV_{iw})$
RV_{infw}	$RV_{infw} = (V_{et}-V_{rw})/(1 - LR_{infw})$
F_n	$F_n = [1-(\%NBV_W/100)]/(1-F_{tw})$, or
F_n	$F_n = (RV_{et} + RV_{dw})/(RV_{et} + RV_{dw}$ + additional deep percolation), or
F_n	$F_n = (RV_{infw})/(RV_{iw})$, when $F_{tw} = 0.0$
RV_{iw}	$RV_{iw} = [(V_{et}-V_{rw})/(1-LR_{infw})(F_n)]/(1-F_{tw})$, or
RV_{iw}	$RV_{iw} = [(V_{et}-V_{rw})/(1-LR_{infw})][1/(F_n)(1-F_{tw})]$, or
RV_{iw}	$RV_{iw} = (V_{et}-V_{rw})/[(1-LR_{infw})(1-F_{tw})(F_n)]$, or
RV_{iw}	$RV_{iw} = RV_{infw} + V_{tw}$
RV_{iw}/RV_{infw}	$RV_{iw}/RV_{infw} = [1/F_n(1-F_{tw})]$
$[N]$	$[N] = (RV_{iw}/V_{et}) = [((1/(1-LR_{infw})(F_n))/(1-F_{tw})]$
RV_{dw}	$RV_{dw} = (LR_{infw})(RV_{infw})$, or
RV_{dw}	$RV_{dw} = [(LR_{infw})/(1-LR_{infw})](V_{et})$, or
RV_{dw}	$RV_{dw} = (LR_{iw})(RV_{iw})$
V_{tw}	$V_{tw} = (F_{tw})(RV_{iw})$
TDV	$TDV = RV_{dw} + V_{tw}$, or
TDV	$TDV = (LR_{iw})(RV_{iw}) + (F_{tw})(RV_{iw})$, or
TDV	$TDV = (LR_{iw} + F_{tw})(RV_{iw})$, or
TDV	$TDV = (LR_{infw})(RV_{infw}) + (F_{tw})(RV_{iw})$
BV_{tw}	$BV_{tw} = [(LR)((V_{et})/(1-LR))]-[(LR_{infw})((V_{et})/(1-LR_{infw}))]$, or
BV_{tw}	$BV_{tw} = [(LR)((V_{et})/(1-LR))]-[(LR_{iw})((V_{et})/(1-LR_{iw}-F_{tw}))]$, or
TBV_w	$TBV_w = V_{et} + RV_{dw} + BV_{tw}$
NBV_W	$NBV_W = RV_{iw} - TBV_W$
C_{infw}	$C_{infw} = [(V_{iw}C_{iw})(1-F_{tw}F_{ctw})]/(V_{infw})$
	use when ignoring LR in calculations; based solely on V_{et}
F_n^*	$F_n^* = [1-(\%NBV_W/100)]/(1-F_{tw})$, or $= (F_n)(1-F_{tw})$
RV^*_{iw}	$RV_{iw} = [(V_{et})/(F_n^*)]/(1-F_{tw})$, or $= (V_{et})[1/(F_n^*)(1-F_{tw})]$

[a] symbols are defined in Table 4a; [b] the general assumption in LR models;
[c] $F_{tw} = (V_{tw})/(V_{iw})$; [d] $F_{ctw} = (EC^{\wedge}_{tw})/(EC_{iw})$

Table 4b. Estimates of Uncertainty in Tailwater and Deep Percolation Volumes [1]						
Estimated Volumes of Tailwater, thousands of acre-feet						
Combined Approach	Mean	Std. Dev.	Confidence Interval 90%, 2-sided CI		Lower Confidence Bounds 90%	Lower Confidence Bounds 95%
Setmire-1 & Rhoades-1	670.4	61.4	562.7	762.3	590.9	562.7
Setmire-2 & Rhoades-1	637.4	65.2	523.2	732.8	554.0	523.2
Estimated Volumes of Deep Percolation, thousands of acre-feet						
Combined Approach	Mean	Std. Dev.	Confidence Interval 90%, 2-sided CI		Upper Confidence Bounds 90%	Upper Confidence Bounds 95%
Setmire-1 & Rhoades-1	132.4	43.8	74.5	214.3	189.5	214.3
Setmire -2 & Rhoades-1	165.4	48.9	102.4	256.0	229.3	256.0

[1] where: CL_{infw}, CL_{surf}, CL_M and CL_{tile} = 117.1, 141.3, 454.5 or 536.8 and 1544.6 mg/L, respectively; volumes of V_{iw} , V_{et}-V_{rw}, total returns, seepage, spillage, M&I and unconsumed rain rain are 2508, 1705, 1079, 114, 99, 30 and 33 KAF, respectively.

Table 6. Effects of Non-Uniformity Compensation on Minimum Non-Beneficial Irrigation and Drainage Volumes[a]

A) Compensation Applied to Both V_{et} and RV_{dw}; $RV_{iw} = [(V_{et})/(1-LR_{infw})(F_n)]/(1-F_{tw})$

F_n[b]	F_{tw}	V_{et}	RV_{infw}[c]	RV_{dw}[c]	RV_{iw}[d]	NBV_W[e]	% NBV_W[e]	V_{tw}[f]	V_{dw}[g]	LF_{iw}[h]	NRV_{dw}[i]	% NRV_{dw}[j]
0.70	0.00	100.000	111.111	11.111	158.730	47.619	30.000	0.000	58.730	0.370	47.620	81.083
0.75	0.00	100.000	111.111	11.111	148.148	37.037	25.000	0.000	48.148	0.325	37.038	76.925
0.80	0.00	100.000	111.111	11.111	138.889	27.778	20.000	0.000	38.889	0.280	27.779	71.431
0.85	0.00	100.000	111.111	11.111	130.719	19.608	15.000	0.000	30.719	0.235	19.608	63.830
0.90	0.00	100.000	111.111	11.111	123.457	12.346	10.000	0.000	23.457	0.190	12.347	52.637
0.95	0.00	100.000	111.111	11.111	116.959	5.848	5.000	0.000	16.959	0.145	5.849	34.489
1.00	0.00	100.000	111.111	11.111	111.111	0.000	0.000	0.000	11.111	0.100	0.000	0.000
1.00	0.05	100.000	111.111	11.111	116.959	5.848	5.000	5.848	11.111	0.095	0.000	0.000
1.00	0.10	100.000	111.111	11.111	123.457	12.346	10.000	12.346	11.111	0.090	0.000	0.000
1.00	0.15	100.000	111.111	11.111	130.719	19.608	15.000	19.608	11.111	0.085	0.000	0.000
1.00	0.20	100.000	111.111	11.111	138.889	27.778	20.000	27.778	11.111	0.080	0.000	0.000

B) Compensation Applied Only to V_{et}; $RV_{iw} = [(V_{et})/(F_n^*)]/(1-F_{tw})$

F_n^*[b]	F_{tw}	V_{et}	RV_{inf}[c]	RV_{dw}[c]	RV_{iw}[d]	NBV_W[e]	% NBV_W[e]	V_{tw}[f]	V_{dw}[g]	LF_{iw}[h]	NRV_{dw}[i]	% NRV_{dw}[j]
0.70	0.00	100.000	111.111	11.111	142.857	31.746	22.222	0.000	42.857	0.298	31.746	74.074
0.75	0.00	100.000	111.111	11.111	133.333	22.222	16.666	0.000	33.333	0.250	22.222	66.667
0.80	0.00	100.000	111.111	11.111	125.000	13.889	11.111	0.000	25.000	0.200	13.889	55.556
0.85	0.00	100.000	111.111	11.111	117.647	6.536	5.556	0.000	17.647	0.150	6.536	37.037
0.90	0.00	100.000	111.111	11.111	111.111	0.000	0.000	0.000	11.111	0.100	0.000	0.000
0.95	0.00	100.000	111.111	11.111	105.263	-5.848	-5.556	0.000	5.263	0.050	-0.5848	-11.111
1.00	0.00	100.000	111.111	11.111	100.000	-11.111	-11.111	0.000	0.000	0.000	0.000	0.000
1.00	0.05	100.000	111.111	11.111	105.263	-5.848	-5.556	5.263	0.000	0.000	0.000	0.000
1.00	0.10	100.000	111.111	11.111	111.111	0.000	0.000	11.111	0.000	0.000	0.000	0.000
1.00	0.15	100.000	111.111	11.111	117.647	6.536	5.556	17.647	0.000	0.000	0.000	0.000
1.00	0.20	100.000	111.111	11.111	125.000	13.889	11.111	25.000	0.000	0.000	0.000	0.000

[a] $LR_{infw} = 0.1$ and tailwater fraction $F_{tw} = 0.00 - 0.20$; [b] F_n and F_n^* are the non-uniformity compensation factors;

[c] $RV_{infw} = (V_{et})/(1-LR_{infw})$, $RV_{dw} = [(LR_{infw})/(1-LR_{infw})](V_{et})]$, assuming complete uniformity ($F_n = 1.0$);

[d] for A) $RV_{iw} = [V_{et}/(1-LR_{infw})(F_n)]/(1-F_{tw})$, for B) $RV_{iw} = [(V_{et})/(F_n^*)]/(1-F_{tw})$;

[e] $NBV_{iw} = (RV_{iw} - TBV_W)$ = minimum non-beneficial irrigation water, % $NBV_{iw} = (100)(NBV_{iw})/(RV_{iw})$; [f] $V_{tw} = (F_{tw})(RV_{iw})$; [g] $V_{dw} = RV_{iw} - V_{et} - V_{tw}$;

[h] $LF_{iw} = V_{dw}/RV_{iw}$; [i] NRV_{dw} = minimum non-beneficial deep percolation = $V_{dw} - RV_{dw}$; [j] % $NRV_{dw} = (100)(NRV_{dw})/(V_{dw})$

Table 13a. IID Water Requirement for 2000-2002 Crop Consumptive Use [a] and EC_{iw} = 1.0909 dS/m						
	volumes in thousands of acre-feet					
	$LR_W{}^b$ = 0.058153			$LR_T{}^b$ = 0.105783		
	tailwater percentages_F_n			tailwater percentages_F_n		
item	5%_0.95	10%_0.95	15%_0.95	5%_1.0	10%_1.0	15%_1.0
$LR_{infw}{}^c$	0.0576	0.0569	0.0562	0.1047	0.1035	0.1022
$LR_{iw}{}^c$	0.0520	0.0487	0.0454	0.0995	0.0932	0.0869
$RV_{infw}{}^d$	1809.5	1808.2	1806.8	1904.8	1902.3	1899.5
$RV_{iw}{}^d$	2004.9	2114.9	2237.6	2005.0	2113.6	2234.7
$RV_{dw}{}^e$	104.2	102.9	101.6	199.5	197.0	194.2
$V_{dw}{}^f$	199.4	198.1	196.6	199.5	197.0	194.2
$NBV_{dw}{}^g$	95.2	95.2	95.1	0.0	0.0	0.0
$V_{tw}{}^h$	100.2	211.5	335.6	100.3	211.4	335.2
$BV_{tw}{}^i$	1.1	2.4	3.7	2.3	4.8	7.5
$NBV_{tw}{}^j$	99.1	209.1	331.9	98.0	206.6	327.7
$BV_{tw} + RV_{dw}{}^l$	105.3	105.3	105.3	201.7	201.7	201.7
$V_{tw} + V_{dw}{}^k$	299.7	409.6	532.3	299.7	408.3	529.4
$BV_W{}^l$	1810.6	1810.6	1810.6	1907.0	1907.0	1907.0
$NBV_W{}^m$	194.4	304.3	427.0	98.0	206.6	327.7
$\%NBV_W{}^n$	9.7	14.4	19.1	4.9	9.8	14.7

[a] for total crop consumptive use of 1,705,289 acre-feet (= $V_{et} - V_{rw}$), where V_{rw} = effective rain = $E_P + T_P$;

[b] LR = LR_W or LR_T, the IID crop-weighted WATSUIT- and Traditional- LR values, respectively;

[c] $LR_{infw} = [(1-F_{tw}F_{ctw})/(1-F_{tw})](LR)$; $LR_{iw} = (1-F_{tw})(F_n)(LR_{infw})$; assuming F_{ctw} = 1.19;

[d] $RV_{infw} = [(V_{et}-V_{rw})/(1-LR_{infw})]$; $RV_{iw} = [(V_{et}-V_{rw})/(1-LR_{infw})][1/(F_n)(1-F_{tw})]$; [e] $RV_{dw} = [(LR_{infw})/(1-LR_{infw})](V_{et})$;

[f] $V_{dw} = V_{iw} - V_{et} - V_{tw}$; [h] $BV_{tw} = \{[(LR)/(1-LR)](V_{et})\} - \{[(LR_{infw})/(1-LR_{infw})](V_{et})\}$;

[g] $NBV_{dw} = RV_{iw} - V_{et} - V_{tw} - RV_{dw}$;

[h] $V_{tw} = (F_{tw})(RV_{iw})$, where F_{tw} is the fraction of tailwater relative to applied irrigation water (RV_{iw});

[i] $BV_{tw} = \{[(LR)/(1-LR)](V_{et})\} - \{[(LR_{infw})/(1-LR_{infw})](V_{et})\}$;

[j] $NBV_{tw} = V_{tw} - BV_{tw}$; [k] $V_{tw} + V_{dw}$ = total volume of drainage water;

[l] BV_W = total volume of beneficial water = crop ET plus required leaching = 1654.293 K acre-feet + $RV_{dw} + BV_{tw}$;

[l] $BV_{tw} + RV_{dw}$ = total beneficial leaching water; [J] $V_{tw} + V_{dw}$ = total volume of drainage water;

[m] NBV_W = total volume of non-beneficial water = $NBV_{tw} + NBV_{dw}$; [n] %NBV = 100 $(NBV_W)/RV_{iw}$;

Table 15. On-Farm Duties and Diversion Volumes of Colorado River Water in IID for Various 2003 Conditions, in acre-feet.

	on-farm duties (volumes)				diversion volumes		
condition	crop ET	deep percolation	tailwater	delivery to headgate	net diversion[1]	return flow credit[1]	total diversion[1]
Reinstated Order[2]	1,705,289	196,647	617,253	2,519,189	3,003,200	96,800	3,100,000
15% tailwater; $F_n = 0.95$	1,705,289	196,647	335,636	2,237,572	2,721,583	87,100	2,808,683
10% tailwater; $F_n = 0.95$	1,705,289	198,103	211,488	2,114,880	2,598,891	83,200	2,682,091
5% tailwater; $F_n = 0.95$	1,705,289	199,408	100,247	2,004,944	2,488,955	79,600	2,568,555

[1] net diversion volume based on 484,011 acre-feet of additional water for duck ponds, fish farms, misc. deliveries and conveyance losses upstream of headgate,; diversion volume = sum of net diversion + estimated return flow credit, which is about 3.2% of net diversion based on the DOI/BOR December 27, 2002 approval letters, as described by Scott (2003b); [2] assumes the increased net diversion volume for the Reinstated Order, compared to the 15%_F_n = 0.95 case, is entirely due to additional tailwater.

Table 3. Uncertainties in Parameter Inputs			
input variable	mean	Std. Dev.	Std. Dev. as % of mean
Concentrations-Setmire, mg/l			
C_{tile}	1544.6	256.6	16.6%
C_M (ave. canals)	454.5	34.5	7.6%
C_M (Alamo River)	536.8	20.7	3.9%
C_{surf} (1.13*125 mg/l)	141.3	12.7	9.0%
Concentrations-Rhoades, mg/l			
C_{tile}	1544.6	256.6	16.6%
C_{infw} or C_{iw}	117.1	14.6	12.5%
Volumes-Setmire, thousands of acre-feet			
Seepage	114	14.3	12.5%
Spillage	99	5.5	5.6%
M&I	30	3.8	12.5%
Rain runoff	33	1.7	5.0%
Total returns	1079	11.9	1.1%
Volumes-Rhoades, thousands of acre-feet			
Delivered On-Farm	2508	62.7	2.5%
Crop ET - Eff. Rain	1705	51.5	3.0%

Table 4b. Estimates of Uncertainty in Tailwater and Deep Percolation Volumes [1]						
Estimated Volumes of Tailwater, thousands of acre-feet						
Combined Approach	Mean	Std. Dev.	Confidence Interval 90%, 2-sided CI		Lower Confidence Bounds 90%	95%
Setmire-1 & Rhoades-1	670.4	61.4	562.7	762.3	590.9	562.7
Setmire-2 & Rhoades-1	637.4	65.2	523.2	732.8	554.0	523.2
Estimated Volumes of Deep Percolation, thousands of acre-feet						
Combined Approach	Mean	Std. Dev.	Confidence Interval 90%, 2-sided CI		Upper Confidence Bounds 90%	95%
Setmire-1 & Rhoades-1	132.4	43.8	74.5	214.3	189.5	214.3
Setmire -2 & Rhoades-1	165.4	48.9	102.4	256.0	229.3	256.0

[1] where: CL_{infw}, CL_{surf}, CL_M and CL_{tile} = 117.1, 141.3, 454.5 or 536.8 and 1544.6 mg/L, respectively; volumes of V_{iw} , V_{et}-V_{rw}, total returns, seepage, spillage, M&I and unconsumed rain rain are 2508, 1705, 1079, 114, 99, 30 and 33 KAF, respectively.

Table 5b. Comparison of Volumes of Tailwater and Deep Percolation Determined by Separate and Combinated Approaches					
chloride concentration, mg/l				volumes of tailwater, KAF	volumes of deep percolation, KAF
CL_{surf}	CL_{infw}	CL_M	CL_{tile}	Setmire & Rhoades-1	Setmire & Rhoades-1
Combined Approach					
141.25	117	454.5	1544.6	670.4 (61.4)*	132.4 (43.8)
141.25	117	536.8	1544.6	637.4 (65.2)	165.4 (48.9)
Separate Approaches					
141.25		454.6	1544.6	683.6 (59.3)	119.6 (59.7)
141.25		536.8	1544.6	617.7 (67.6)	185.6 (68.1)
	117		1544.6	657.1 (92.2)	145.2 (35.3)

* value within ( ) is standard deviation